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MODIFICATION AND VERIFICATION OF AN ANTENNA DESIGN FOR THE PETITE AMATEUR NAVY SATELLITE (PANSAT) USING NEC

by

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June 1995

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MODIFICATION AND VERIFICATION OF AN ANTENNA DESIGN FOR PETITE AMATEUR NAVY SATELLITE (PANSAT) USING NEC

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In this thesis, a tangential turnstile antenna is modified and verified for the Petite Amateur Navy Satellite (PANSAT). The Numerical Electromagnetics Code (NEC) is used to model the antenna system. The final design provides a circularly polarized, omnidirectional radiation pattern with maximum nulls of -2.7 dBi. Two alternative antenna feed systems are proposed.

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I. INTRODUCTION

A. OBJECTIVES

The objective of this thesis is to verify the current design of the Petite Amateur Navy Satellite (PANSAT) Antenna System and suggest modifications as necessary. The Numerical Electromagnetics Code (NEC) is used to model the PANSAT antenna system.

This thesis also describes the integration of the Launch Vehicle Interface (LVI), and reports the results of subsequent electromagnetic performance analysis. The original length, orientation and the position of antenna elements on the PANSAT body were modified until they met specifications. The performance analysis consisted of evaluation of radiation patterns, antenna input impedance and polarization of the antenna system and was repeated after each new modification of antenna elements. The scope of this thesis is limited to describing the modification, optimization, verification of the antenna system and the design of an antenna feed system for PANSAT.

B. THE PANSAT PROJECT AT NPS

The PANSAT program at the Naval Postgraduate School was started in 1989 and sponsored by the Navy Space Systems Division (N63). Since 1989, PANSAT has been under construction by the Space Systems Academic Group (SSAG).

Over the years, expensive, complex satellites have been replaced by small, inexpensive Low Earth Orbit (LEO) satellites. LEO satellites can provide real time, wide area communications through the use of inter-satellite networks, which can transfer information before relaying it to the ground station.

Satellite communications lost as a result of hostile actions are hard to replace in a very short time, but can be recovered by small low cost LEOs that can be quickly developed and produced.

PANSAT is a "stepping stone" for development of small LEO satellites [Ref. 1]. The PANSAT project enhances the educational experience of NPS students and provides educational opportunities to research space related topics. It also provides the opportunity to design and improve space-based hardware. Learning opportunities continue after the launch of the satellite, by providing a vehicle for satellite communications experiments. PANSAT is a 150 pound, 16 inch diameter, 26 sided polyhedron body designed for launch as a space shuttle secondary payload. Figure 1 shows the shape of the space craft without antennas.

PANSAT is a small spread-spectrum communications satellite. It is a tumbling spacecraft that will be completed in 1996, and will most likely be launched using the space shuttle Get Away Special (GAS) canister under the HitchHiker program. The launch will place PANSAT in a low earth orbit with an inclination of 28 degrees.

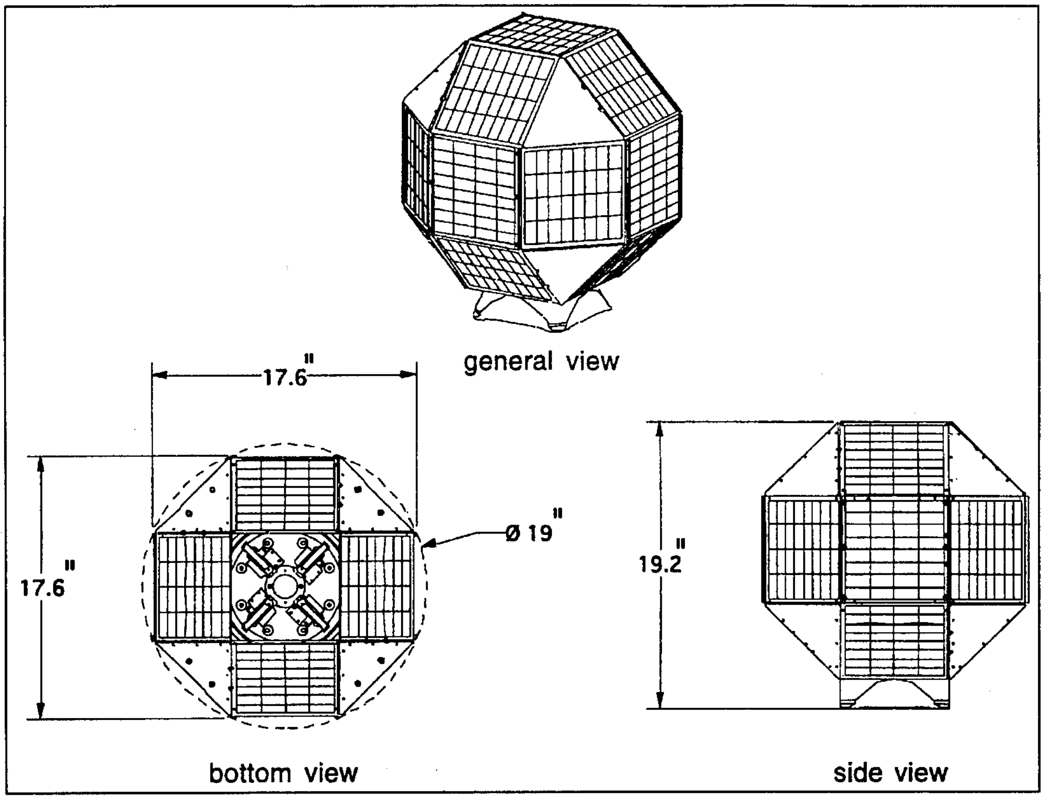

Figure 1. PANSAT General, Bottom, and Side Views.

PANSAT is constructed of 6061-TG aluminum. The 19-inch diameter spacecraft is built around the main load bearing cylinder, which connects to the main lower equipment plate. The other end of this cylinder is the Launch Vehicle Interface (LVI).

The communications payload of PANSAT consists of a direct sequence, spread spectrum (DS/SS), differentially encoded binary phase shift-keyed (DBPSK) communications system, which is the first DS/SS system designed for amateur radio (HAM) use. It has an operating center frequency of 436.5 MHz, a bit rate of 9,600 bps and 4 MB of memory for storage, and is able to send and receive messages as it passes overhead for store-and-forward communications. The AX.25 amateur radio data link

layer protocol (based on CITT X.25 protocol) will be utilized in the PANSAT communications link.

PANSAT has many potential applications. By virtue of DS/SS, it has a low probability of intercept, an important feature for downed-pilot rescues. It can provide logistic traffic, over-the-horizon communication, and communications with remote areas.

The PANSAT includes the following major subsystems:

- Digital Control Subsystem (DCS)
- Electrical Power Subsystem (EPS)
- Communications Subsystem (COMM)
- Ground Control

The DCS provides overall control of PANSAT, monitoring and controlling the EPS and COMM subsystems by transmitting operating data to and receiving instruction from ground controllers. The EPS consists of seventeen 256 cm^2 solar panels and two batteries to store and provide power for satellite systems The COMM system consists of two fully redundant transceivers. The EPS provides +15V and +5 V power levels, and the DCS controls power. The COMM subsystem sends uplinked messages to the DCS for processing and receives messages downlinked from the DCS. Figures 2 and 3 show the subsystem configuration and location of PANSAT.

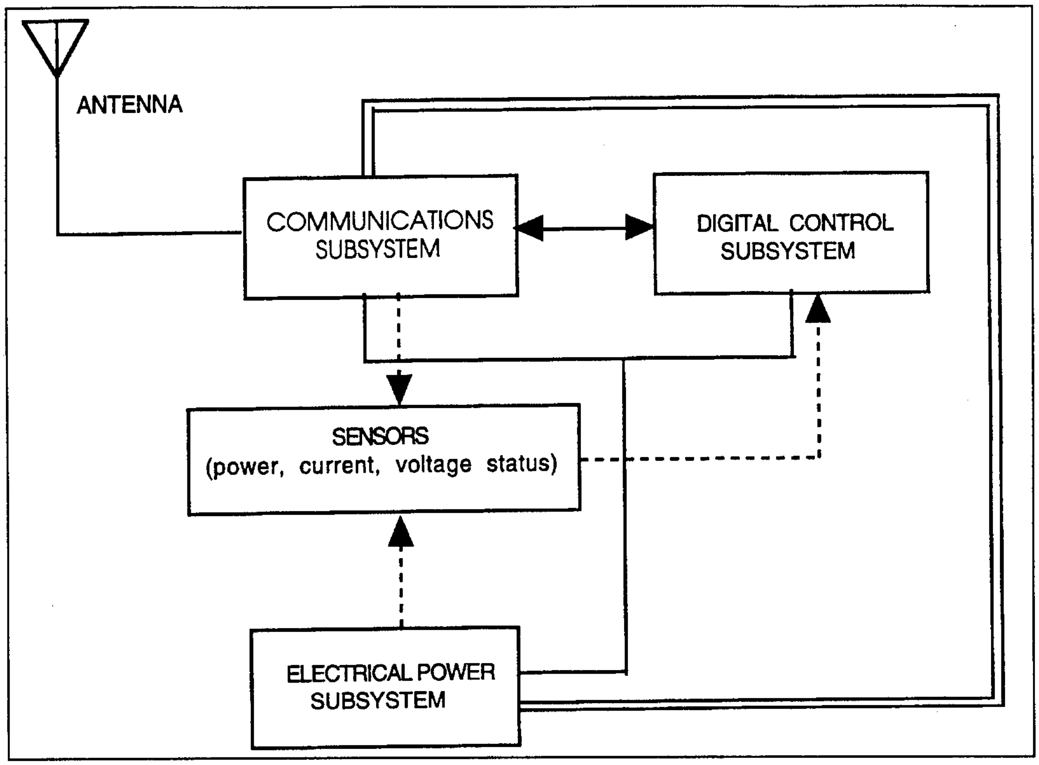

Figure 2. PANSAT Subsystem Description.

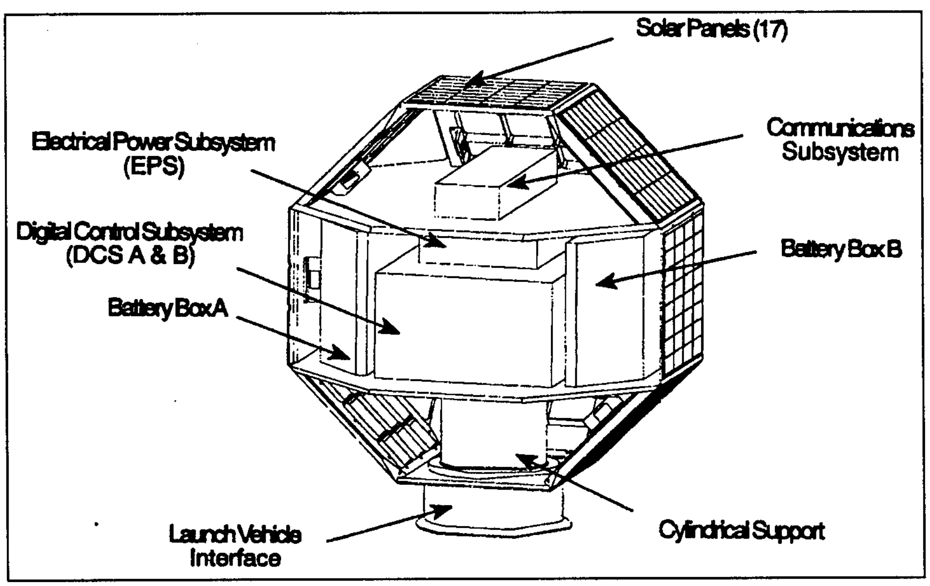

Figure 3. PANSAT Subsystem Locations.

C. DEVELOPMENT OF THE PANSAT ANTENNA SYSTEM

A design for the PANSAT antenna system was proposed by Daniel A. Ellrick in his NPS Thesis, “An Antenna Design for PANSAT Using NEC”, in June, 1991. PANSAT is a tumbling satellite; it doesn’t have any attitude control or propulsion system. As a result, the satellite antenna system must be as omnidirectional as possible. Ellrick noted that the ground stations utilize simple linearly polarized antennas, which are common for amateur radio users. Utilizing a circularly polarized antenna will help avoid large polarization losses that occur between linearly polarized ground antennas and linearly polarized signals coming from the satellite at arbitrary angles. A turnstile antenna has been proposed, among other candidates such as the Hula-Hoop antenna and the resonant quadrifilar helix. Ellrick regarded the Turnstile Antenna as “the most promising approach, based on its simplicity and flexibility” [Ref. 1].

Since Ellrick’s work, the PANSAT’s physical structure has been modified by adding the Launch Vehicle Interface (LVI). Integration of the LVI will affect the performance of the current design, and the first goal of this thesis is to integrate the LVI into the NEC model. After this step, the results of performance analysis will determine the succeeding steps.

The PANSAT antenna system must meet the following electrical specifications:

- Minimum antenna gain of -3 dBi.
- Approximately omnidirectional radiation pattern.
- Circular polarization with an axial ratio greater than 0.42.

- Operational bandwidth of 2.5 MHz with center frequency of 436.5 MHz.

Mechanical specifications for the antenna system must also be addressed. The rectangular parts of the PANSAT body are covered with solar cells. Consequently, these rectangular parts are not suitable for mounting of antenna elements, which should not shade the solar cells. Therefore, the optimum locations for antenna elements are the triangular parts of the PANSAT body. PANSAT is to be launched from a shuttle Get Away Special (GAS) canister. The maximum allowable clearance between the antenna element end point and the inner wall of the GAS canister is 0.5 inches. The available volume for antennas is therefore limited. Figure 4 shows the triangular mounting surfaces and the general arrangement of the PANSAT body in the GAS Canister.

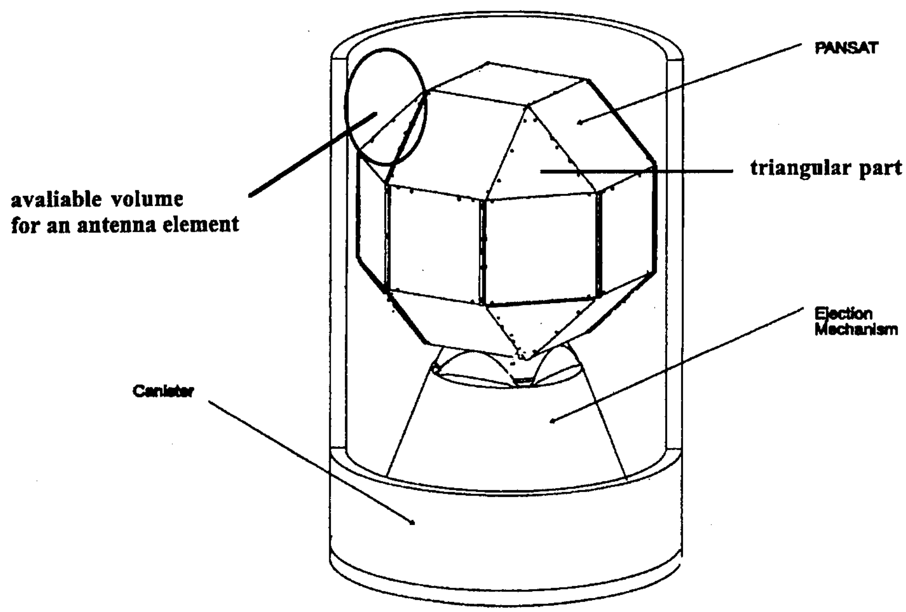

Figure 4. Triangular Surfaces and General Arrangement of the PANSAT in the GAS Canister.

D. OPTIMIZATION OF THE ANTENNA DESIGN

The PANSAT antenna system is improved through a series of steps. Each step is determined by the results of the previous step. First, NEC is run for the PANSAT model without the LVI. The LVI is added as a requirement of change of satellite geometry and NEC is rerun. The results of the performance analysis are then compared.

Three physical features of the antenna elements to be modified, are listed below in the modification order:

- Location.
- Angle orientation.
- Element length.

Since change in the location of antenna elements affects the performance more than other two, it is the first modification. After the location is decided, the next step is to orient the antenna elements in the best angle configuration. Variations of element lengths change only the input impedance, thus it is the last modification. After the locations and angle orientations are found, the lengths of antenna elements can be changed for the desired impedance.

In the first modification, the goal is to find locations where the worst nulls are better than -3 dBi. For each location, the antenna radiation pattern, axial ratio, directive gain, and antenna input impedances are calculated. This process continues until element locations which produce the desired performance are found.

Second, the orientation angle of antenna elements is changed to find the optimum gain. This goal is to produce nulls no worse than -3dBi.

In the third modification the length of antenna elements is varied and the input impedance of antenna elements is noted. This modification is for finding the real part of the input impedance equal to 50Ω or the imaginary part equal to 0. An antenna feed system is then designed, based upon on the input impedance of the antenna elements.

II. THE TANGENTIAL TURNSTILE ANTENNA SYSTEM

A. TANGENTIAL TURNSTILE ANTENNA

If two-half wave dipoles with equal magnitude and current in phase quadrature are crossed, this arrangement can produce a circular pattern at broadside.

Two crossed half-wavelength dipoles, fed in phase progression at their centers is called a "turnstile antenna". This configuration results in an almost omnidirectional broadside radiation pattern with nearly circular polarization [Ref. 2], because two crossed half-wavelength dipoles will fill in the "donut hole" in the radiation pattern of a single dipole.

For satellite applications, four monopoles mounted on the satellite body, spatially perpendicular to each other, can provide the same radiation pattern and polarization [Ref. 1]. Figure 5 shows a turnstile antenna on a cylindrical body.

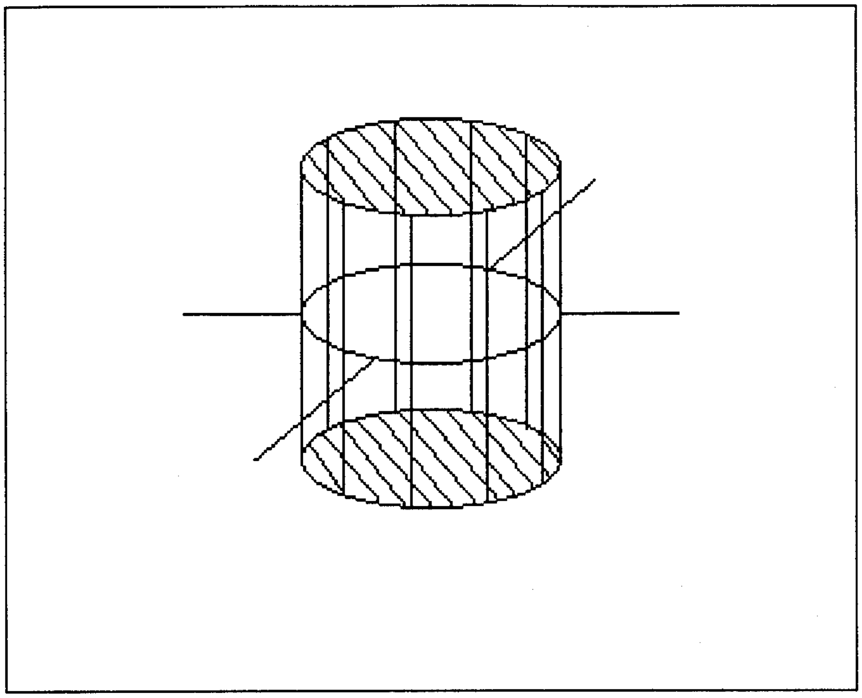

Figure 5. The Representation of a Turnstile Antenna on a Cylindrical Body.

A tangential turnstile antenna is formed after tilting the four monopole antenna elements upward or downward, and then rotating all of the elements 90° clockwise or counter clockwise. Figure 6 shows the upward raised antenna elements on the XZ and YZ planes.

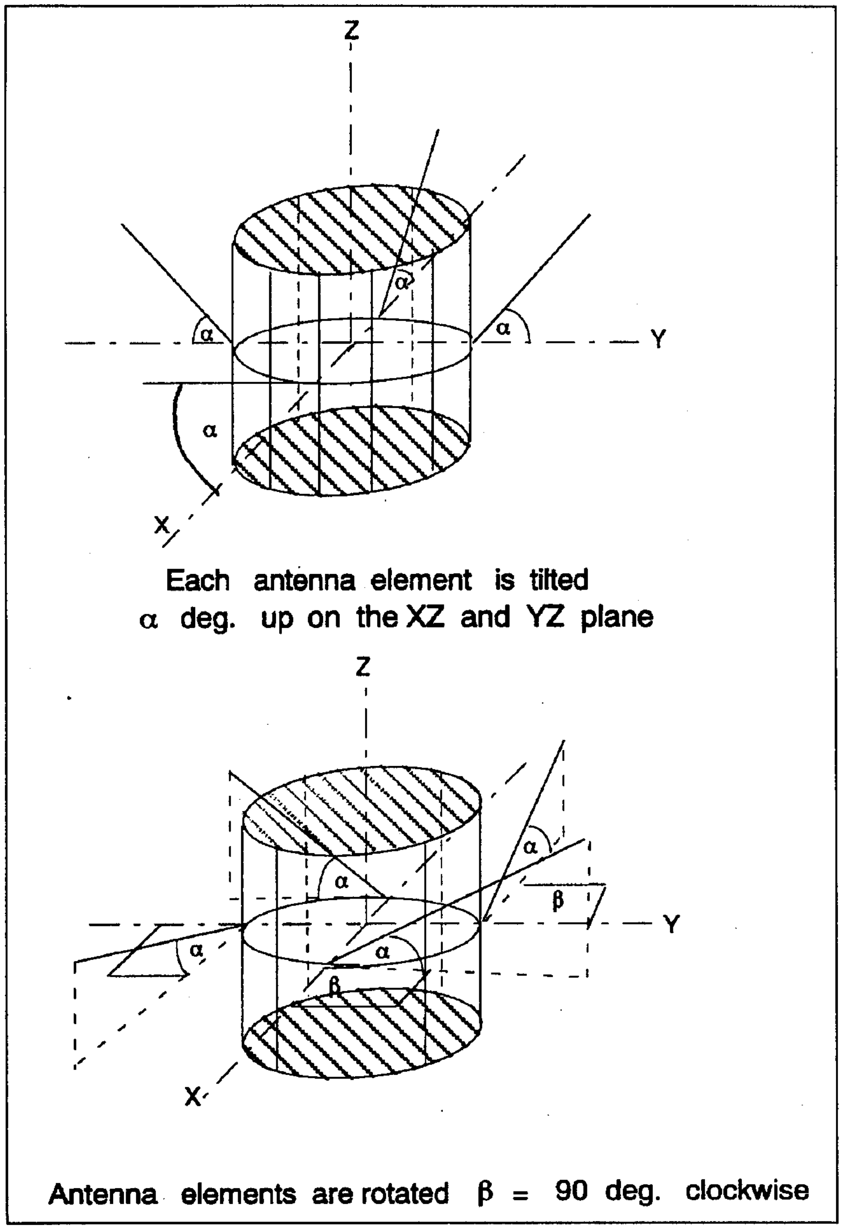

Figure 6. Formation of a Tangential Turnstile Antenna.

B. LVI INTEGRATION

After meeting with the engineers on the PANSAT team, a wire grid numerical model of the LVI was developed as detailed in the subsequent paragraphs (see Figure 7). Each wire is divided into segments. Wire segment sizes are chosen according to predetermined guidelines to assure accuracy of results. Increasing the number of segments beyond some number does not contribute to the results, but rather increases computation time.

The wires should follow the physical outline of the structure as closely as possible. There is no explicit restriction for the angle of intersection of wire segments in NEC. The center of one wire segment should not approach another wire segment closer than a distance greater than the sum of the radii of the two wire segments [Ref. 3]. The length of the wire segments should be less than 0.1λ at the desired frequency. The radius of wires in the wire grid is to be adjusted to meet the equal area rule for flat surfaces of the LVI [Ref. 3]. Piece-wise linear wire segments are used for round, curved surfaces.

Using NEC guidelines, the LVI NEC model is constructed. The first model has 186 segments on 125 wires. This LVI model is added to the PANSAT model and NEC is run. The number of wires is then decreased and the results of the NEC output files are compared. This procedure continues until the optimum number of segments and wires is found. When the segment number reaches 108 on 104 wires, it is observed that the performance of the entire model stabilizes.

Figure 6 shows the side and top wires of the final NEC wire grid model of the LVI.

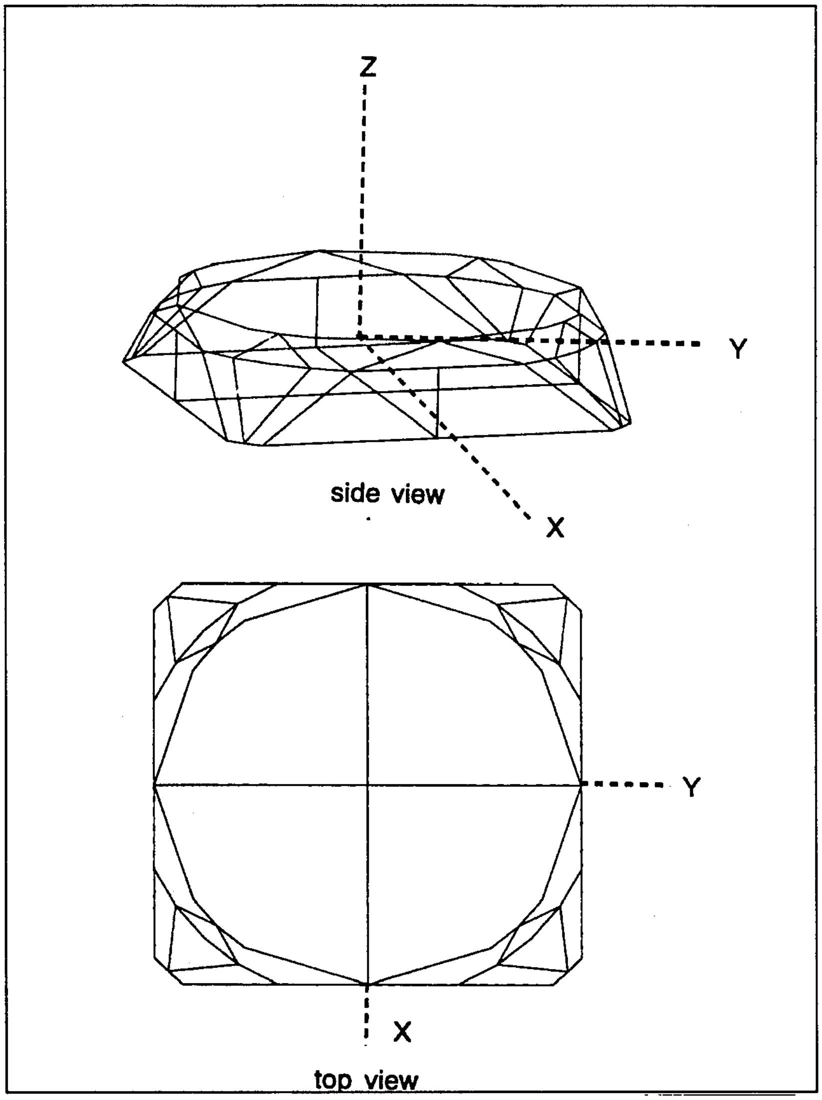

Figure 7. Side and Top View of LVI Wire Grid Model.

Table I shows the comparison of NEC modeling guidelines as applied to the model of the LVI.

NEC GUIDELINES	LVI Model
Segment length < 0.1λ	Segment length < $.079\lambda$
Distance between the centers of two approaching segments > sum of the radii of these approaching segments	Verified
Equal area rule	Verified for flat surfaces

Table I. Comparison of NEC Guidelines Used in the Model of the LVI

The final NEC wire grid model for PANSAT consisted of 488 segments on 296 wires. Addition of extra wires to the wire-grid model does not affect the nulls, gain or impedance of the current design, except for increasing the computation time tremendously. The average gain changed from 1.00 to 0.96, and the worst null changed from -3.5 to -3.8 dBi during adjustments of wire numbers and wire segments.

After the final PANSAT wire grid model with the LVI is developed and NEC output results are recorded, the model for PANSAT without the LVI is also run for comparison of the performance with and without the LVI. Figure 8 depicts the location of antenna elements on the PANSAT body with the LVI.

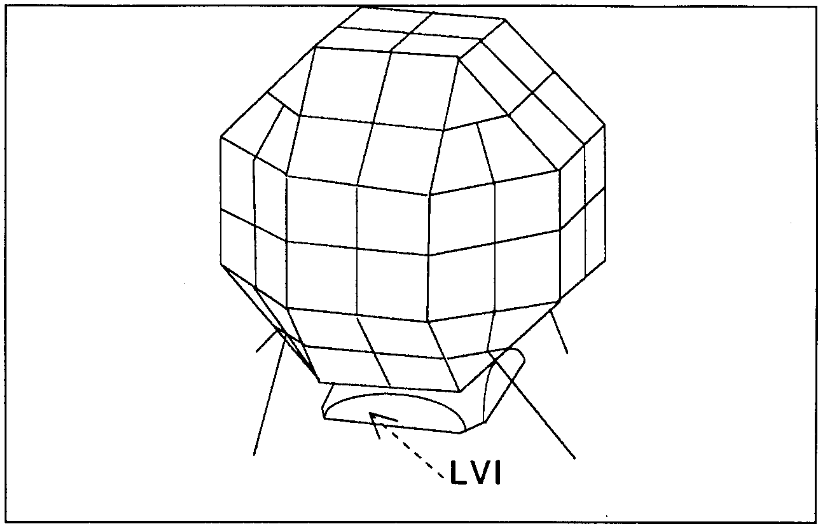

Figure 8. Location of Antenna Elements on PANSAT with the LVI.

The model with the LVI shows the worst null is -3.8 dBi. It provides approximately circular polarization with an average axial ratio of 0.5 and a radiation pattern that is almost omnidirectional. The deterioration of the worst null is the main difference found in the comparison of Table II.

Parameter	Before LVI	After LVI
Worst null	-3.06 dBi	-3.8 dBi
Axial Ratio Minimum	0.0007	0.00073
Axial Ratio Maximum	0.99	0.99
Axial Ratio Average	0.46	0.49
Polarization	Elliptical	Elliptical
Antenna Input Impedance (for the same length)	72.3 + j 0.2Ω (each antenna element)	65.4 + j 8.5Ω (each antenna element)
Average gain	.96	.96

Table II. Comparison of Key Parameters of Designs before and after the LVI.

The LVI produced a worst case null 0.74 dB deeper than without the LVI. When the above results are compared with PANSAT antenna specifications, the LVI addition meets the performance requirements except for the worst null, which should not exceed -3 dBi.

If feed loss and other unpredicted loss exceeds 3 dB, the minimum gain of the antenna system would be less than -6 dBi. To prevent this, the minimum gain of the antenna needs to be improved.

C. MODIFICATION AND OPTIMIZATION OF THE ANTENNA DESIGN

The antenna system must be modified, and its performance optimized to meet the -3 dBi maximum null requirement by varying the following parametrers:

Independent Parameters:

- Position of the antenna elements on the PANSAT body.
- Angle between the antenna elements and the PANSAT body and angle of one element relative to the other elements.
- The length of the antenna elements.

Dependent Parameters:

- Maximum, minimum directive gain.
- Input impedances of antenna elements.
- Axial ratio.

In the modification process, one of the independent parameters is changed while other independent parameters are kept fixed. The dependent parameters are checked for each change in independent parameters. The goal is to find the values of independent parameters which most closely meet antenna performance specifications.

Adjustments in the above parameters have different effects on the performance of the antenna system. After a few experiments, it is determined that position and angle of the antenna elements relative to the body of the PANSAT and each other have major impact on directive gain minima. Increases or decreases in length will change the input impedance more than the gain.

1. Location of Antenna Elements

The angle of the antenna elements is fixed, and their locations on the PANSAT body are moved from the LVI side to the center of the upper edge of triangular surfaces on the side opposite the LVI. Antenna element length is 0.167 m, with radius 0.0045 m. The angle between antenna elements and the XY plane is 45° and each antenna element is rotated 90° clockwise. This is the first location (Figure 9).

In this case a minimum gain of -8.8 dBi, and an input impedance of 45.2+j2.8Ω are observed, with an average gain of 0.88. Minimum and average gains are low. The antenna elements have four segments, and the source is on the segment at the connection point to the body. Adjacent segments are 8.5% different in length. The antenna elements are then divided into five segments, and the source is on the second segment from the connection point, so that segments adjacent to the source have the same length as the source segments. The second run produces a minimum gain of -8.08 dBi, input impedance of 47.9+j5.3Ω, and an average gain of 0.98. Minimum gain is still low. As a check on the accuracy of the NEC solution, the average gain and element current were checked. Average gain was found close to unity as it should be and the element currents were found to be equal in amplitude as they should be for the symmetric drive which was applied. The progressive element phase shifts of 90° are cycled through each element and performance is checked for symmetry, which is shown to be valid.

The second trial location of the antenna elements is on the intersection of two rectangular patches between two triangular surfaces at four sides (Figure 10). In this case, minimum gain is -14.5 dBi which is worse than minimum of the first location (Figure 9).

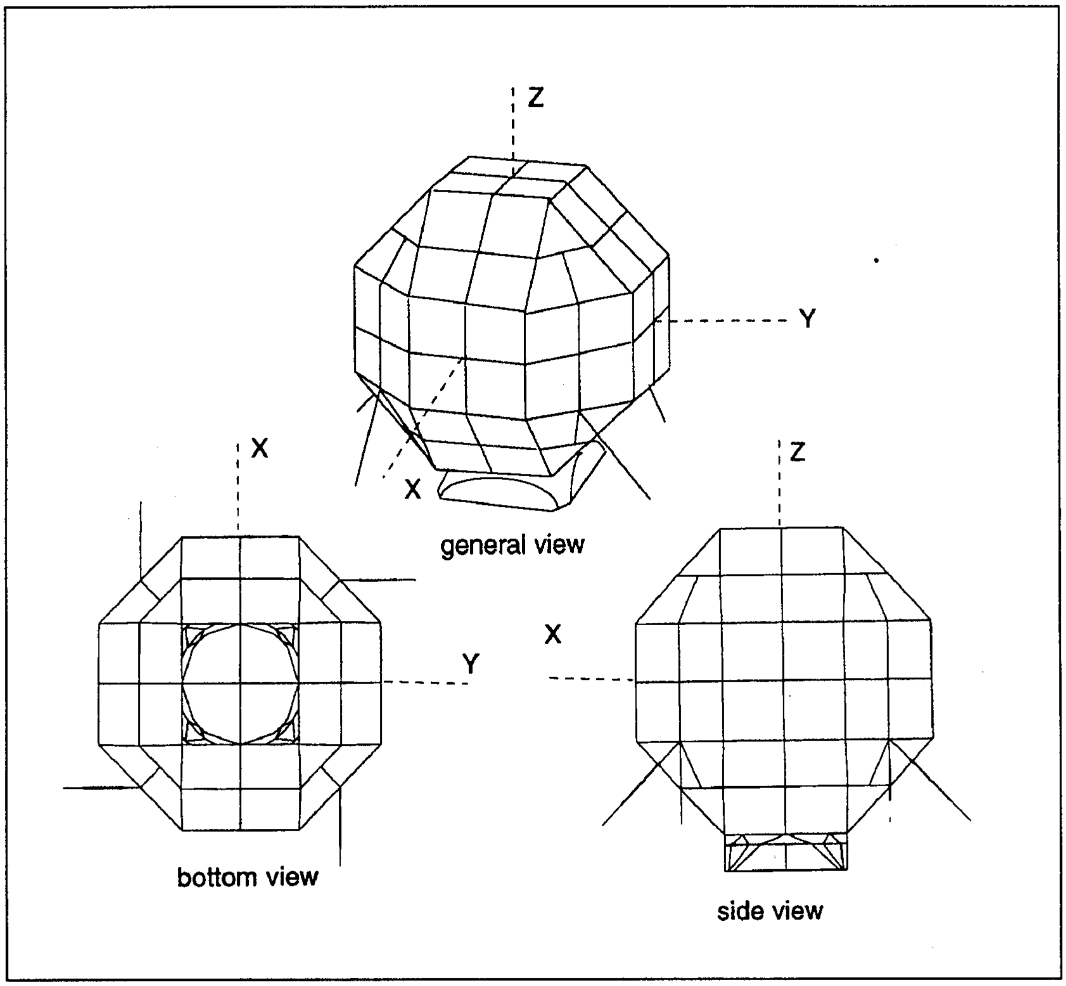

Figure 9. First Location of Antenna Elements.

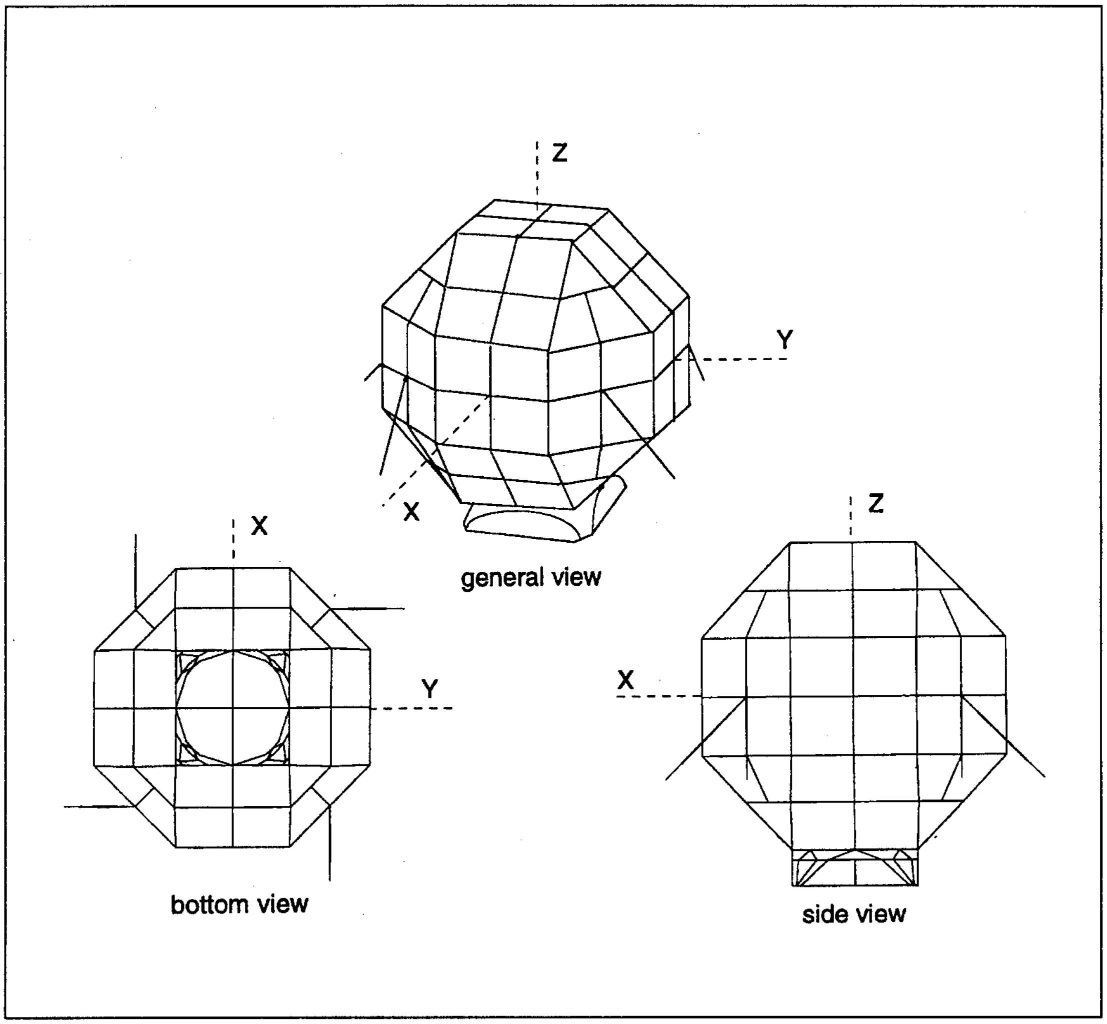

Figure 10. Second Location of Antenna Elements.

At this second trial location antenna elements are raised upward with the symmetric angle orientation as shown in Figure 11. The minimum gain of the antenna system becomes -13.6 dBi.

At the other rectangular intersection locations, the worst nulls are not any better than the worst null observed at the second trial locations.

The third trial location is the upper triangular parts of PANSAT. First, antenna elements are placed at the lower edge of the triangles (Figure 12). Antenna elements are oriented as in the previous example, and minimum gain becomes -6.85 dBi, an improvement. Input impedance is 47+j1.9Ω with an average gain of 0.98. The improvement in worst null provides encouragement to try more triangular locations.

Next, elements are moved upward one fourth of the distance between the middle lower edge of the triangle and its vertex. In this case, the worst null becomes -4.2 dBi, with an average gain of 0.97. Antenna input impedance is 59.3+j5.04Ω. Antenna elements are then moved upward, as before, to a location almost in the center of triangles (Figure 13). The minimum gain is -2.74 dBi, input impedance is 73+j4.5Ω, and average gain is 0.98.

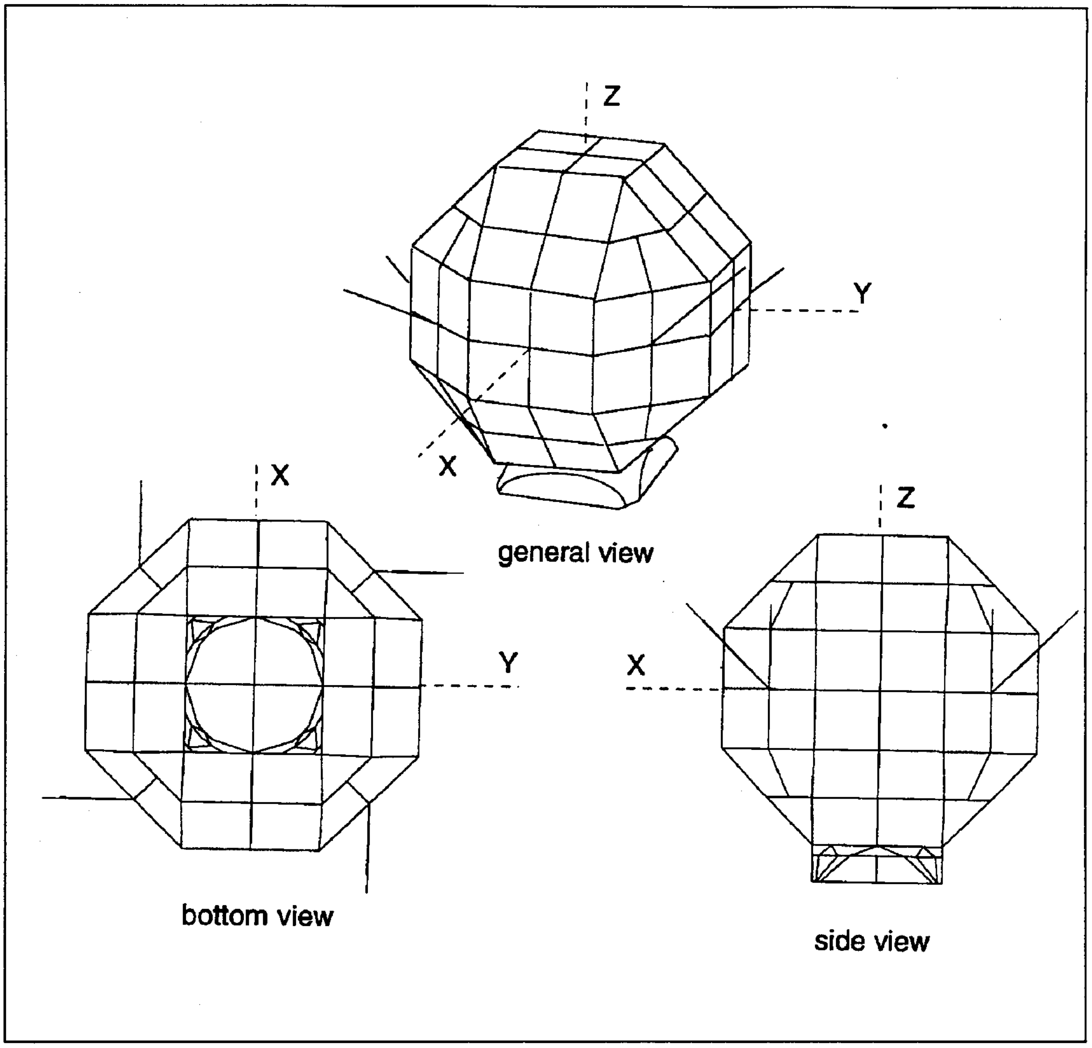

Figure 11. New Orientation of Antenna Elements at the Second Location.

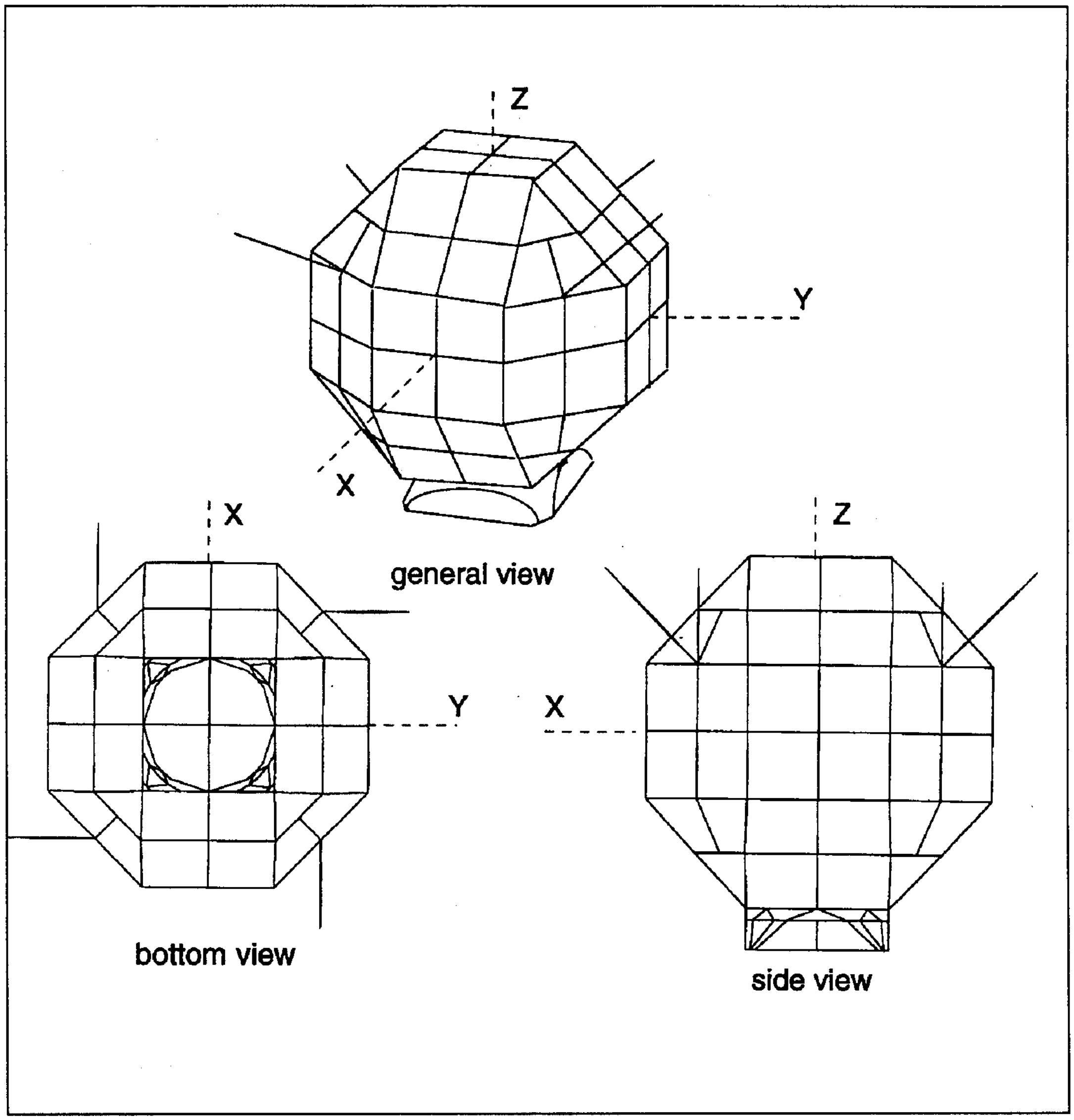

Figure 12. Third Location of Antenna Elements.

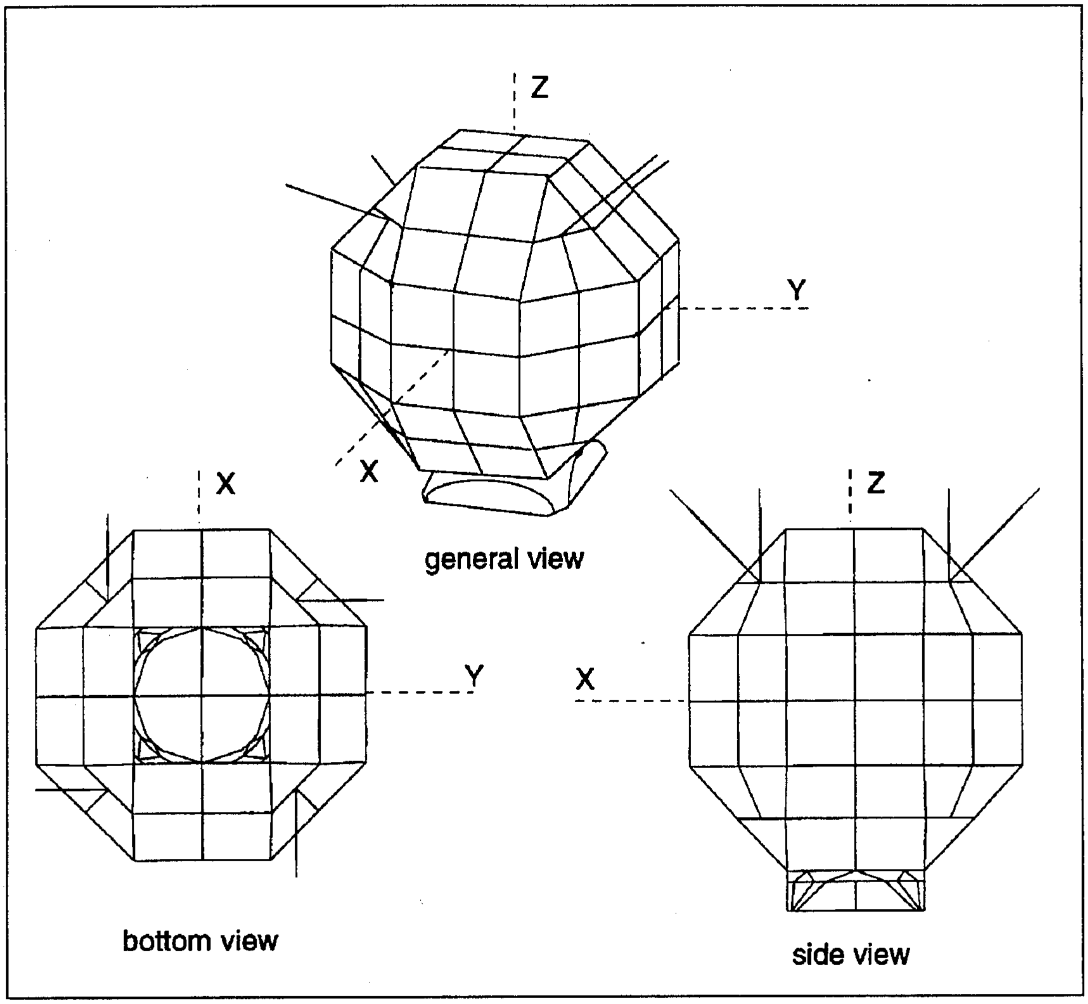

Figure 13. Fourth Location of Antenna Elements.

The antenna elements are then moved to points between the upper corner and the center of the triangles to study changes in the worst null, in this case -2.17 dBi. Input impedance is 94.3+j24.4Ω, with an average gain of 0.94.

The radiation pattern and polarization of the antenna system is checked for each position of the elements. The current distributions on the PANSAT body and antenna elements are stable. These results meet the specifications. Therefore, the antenna elements will be mounted at these points.

2. Angular Orientation of the Antenna Elements

After the location of the antenna elements on the PANSAT body is found, the next task is to find the best orientation angles. In spherical coordinates, the antenna elements form two angles, "angle θ" from the z-axis and "angle ϕ" from the x-axis (Figure 14).

Antenna system performance is tested by changing the angles while keeping the position, the length, and the radius of antenna elements constant. Physically, the geometry of the satellite limits the maximum change in angle. For angle changes in the ϕ plane, only changes for the 0° phase feed element are mentioned in following sections, the other elements being tilted in 90° progressions. Angles from 0° to 135° in the θ plane, and angles from 0° to 170° and from 0° to -135° in the ϕ plane, are tested.

First, an angle change in θ is tested at $\phi = 0$, then ϕ is varied for fixed θ.

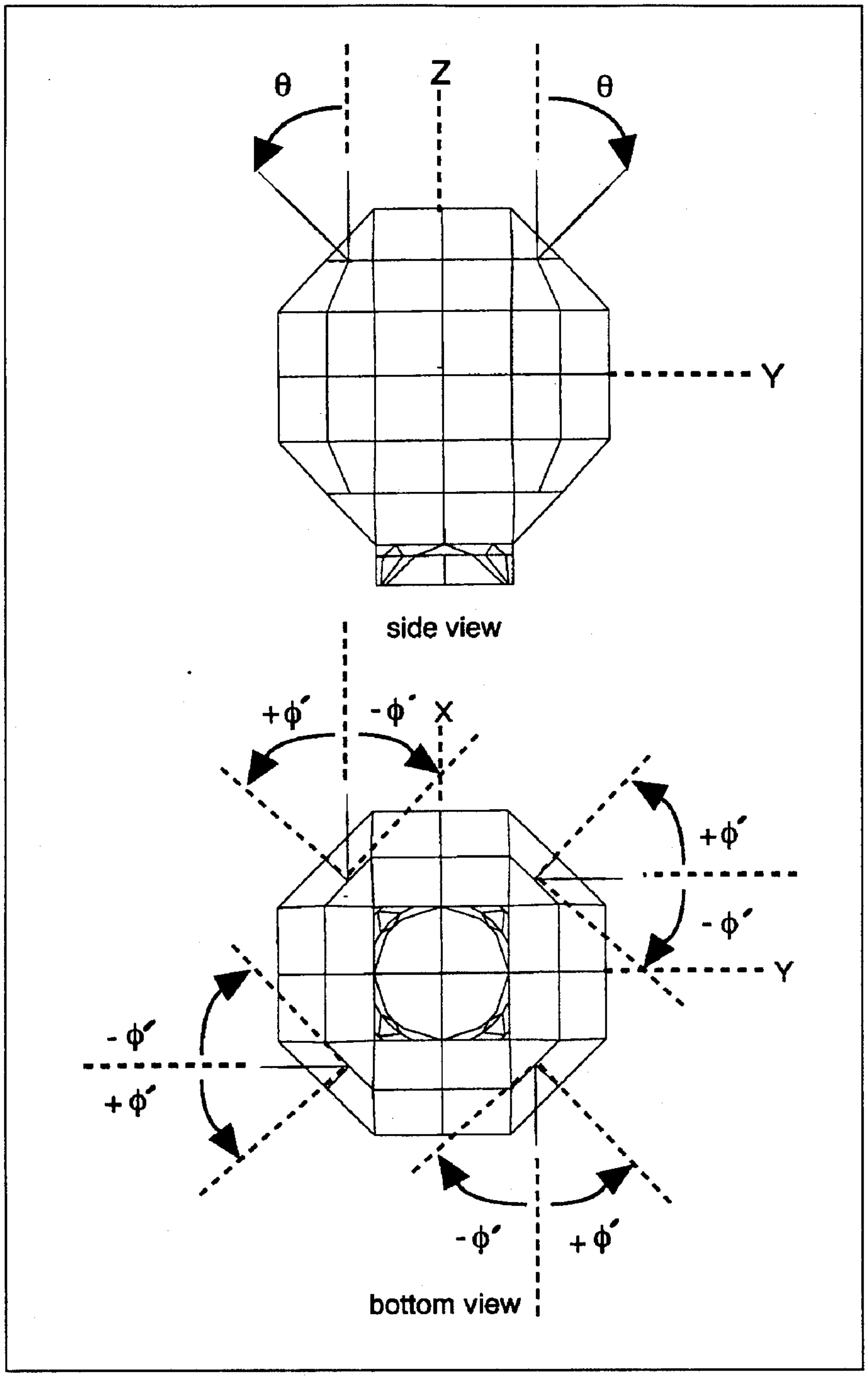

Figure 14. Orientation of Antenna Elements in The θ and φ Planes.

For each angle, the dependent parameters (input impedances, minimum, and maximum) are checked while radiation patterns are plotted. In the θ plane, angles up to 55° produce no nulls exceeding -3 dBi. Input impedances and average gain values are about 45-j5 Ω and 0.95, respectively. As a result, angles 0° to 55° in θ and 0° in ϕ are close to the specifications for the PANSAT antenna system. However, when the radiation patterns are compared, the antenna with $\theta = 45°$ has the most omnidirectional pattern, and is the angle of choice. Figure 15 shows the orientation of antenna elements for θ = 45° and ϕ = 0°, while Figure 16 shows the radiation pattern of the antenna system seen at θ = 90° and ϕ = 45°.

The antenna elements are tilted $+\phi'$ and $-\phi'$ degrees from the position of antenna elements at ϕ = 0°, 90°, 180°, 270° with θ at 45°. For $+\phi'$ angles, from 0° to 20°, the worst nulls do not exceed -3 dBi. Another angle which gave the same performance is ϕ' = 150°, with an average gain of 1.03. Beyond 150° the gain increases and the segments of antenna close to the antenna-body connection point begin to enter into the volume of the body segments on the PANSAT wire grid which establishes a limit on ϕ'.

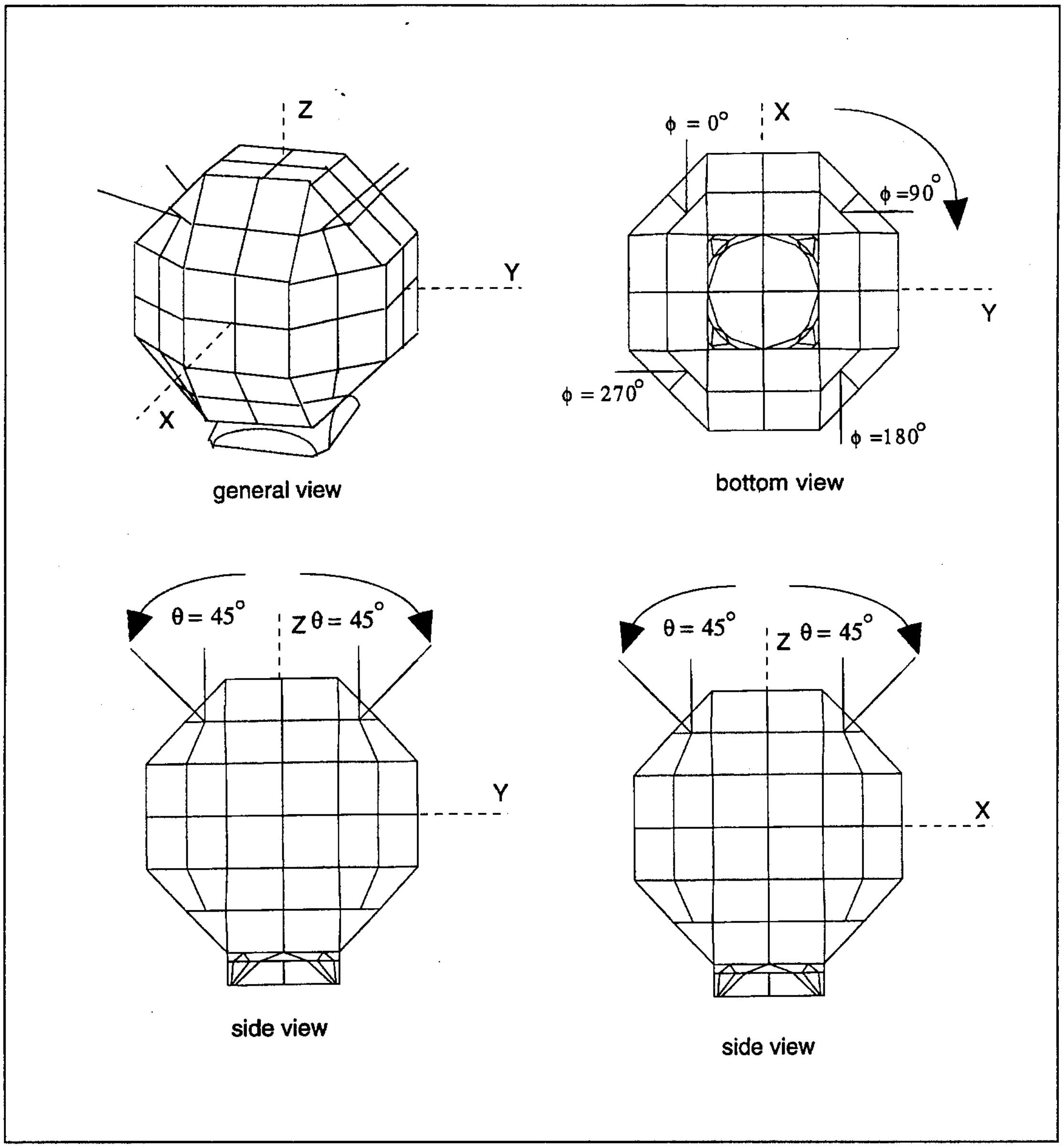

Figure 15. Orientation of Antenna System for θ = 45°.

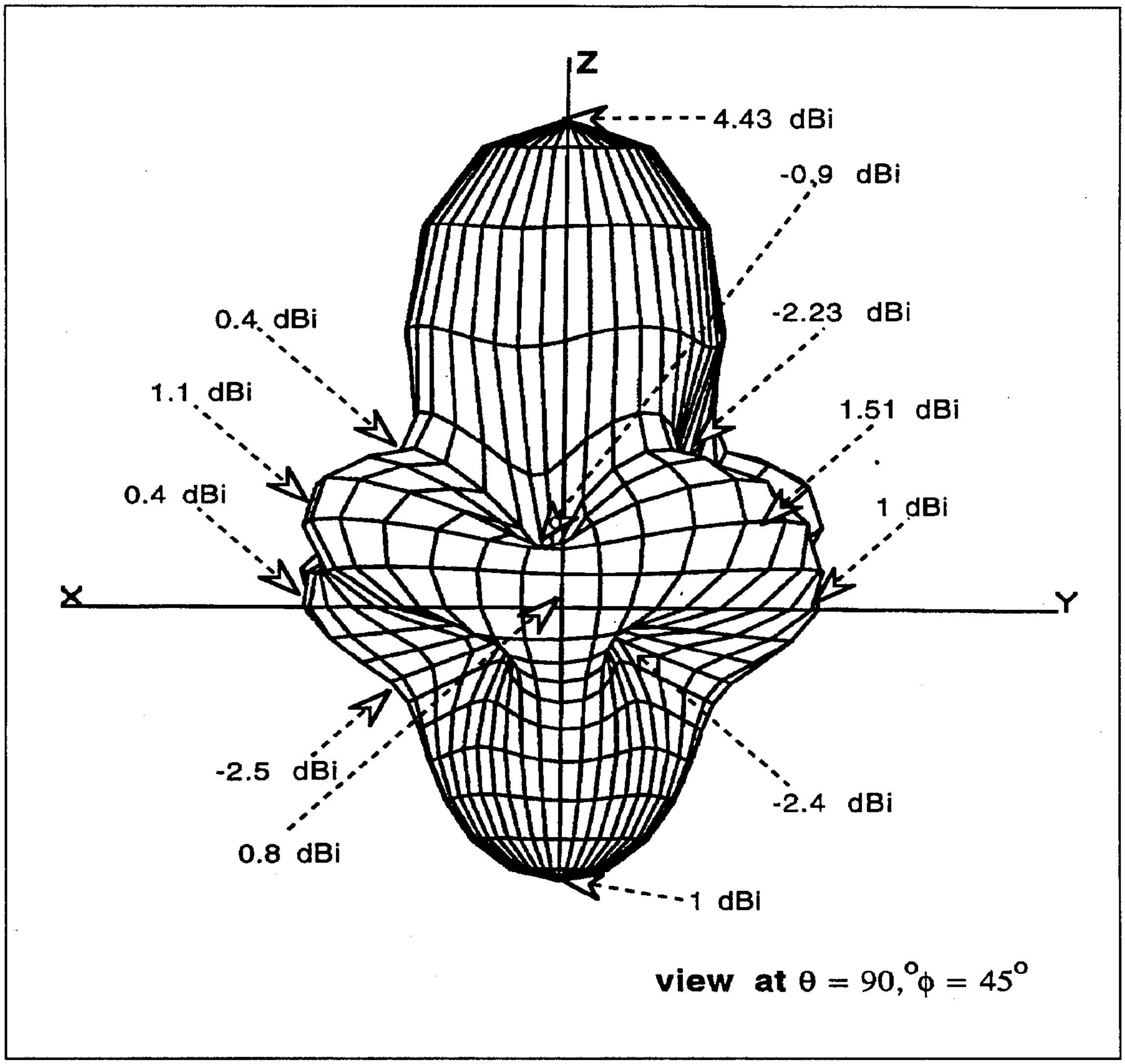

Figure 16. The View of Radiation Pattern for the Antenna System of Figure 15

For $+\phi'$ angles, from 0° to 55°, the worse null is less than -3 dBi, with θ at 45° (Figure 17).

The antenna elements could not be tilted more than $\phi' = 55°$, because the antenna segments close to the connection point began to enter the volume nearby wire grid segments. Therefore, θ is changed from 45° to raise the antenna element in + z direction. Table III shows the ϕ' angles at which the worst null is better than -3 dBi with θ at 45°.

θ (deg.)	**ϕ' (deg)**	**Worst Null (dBi)**	**Average Gain (dB)**
50	70	-2.8	1.05
55	75	-2.7	.96
	80	-2.5	.97
	85	-2.4	.98
	90	-2.2	1.01
75	90	-2.2	.91
80	85	-2.0	.92
	90	-2.0	.92
	100	-2.0	.92
	135	-2.5	.92

Table III. Performance for Tested Tilt Angles in the ϕ Direction.

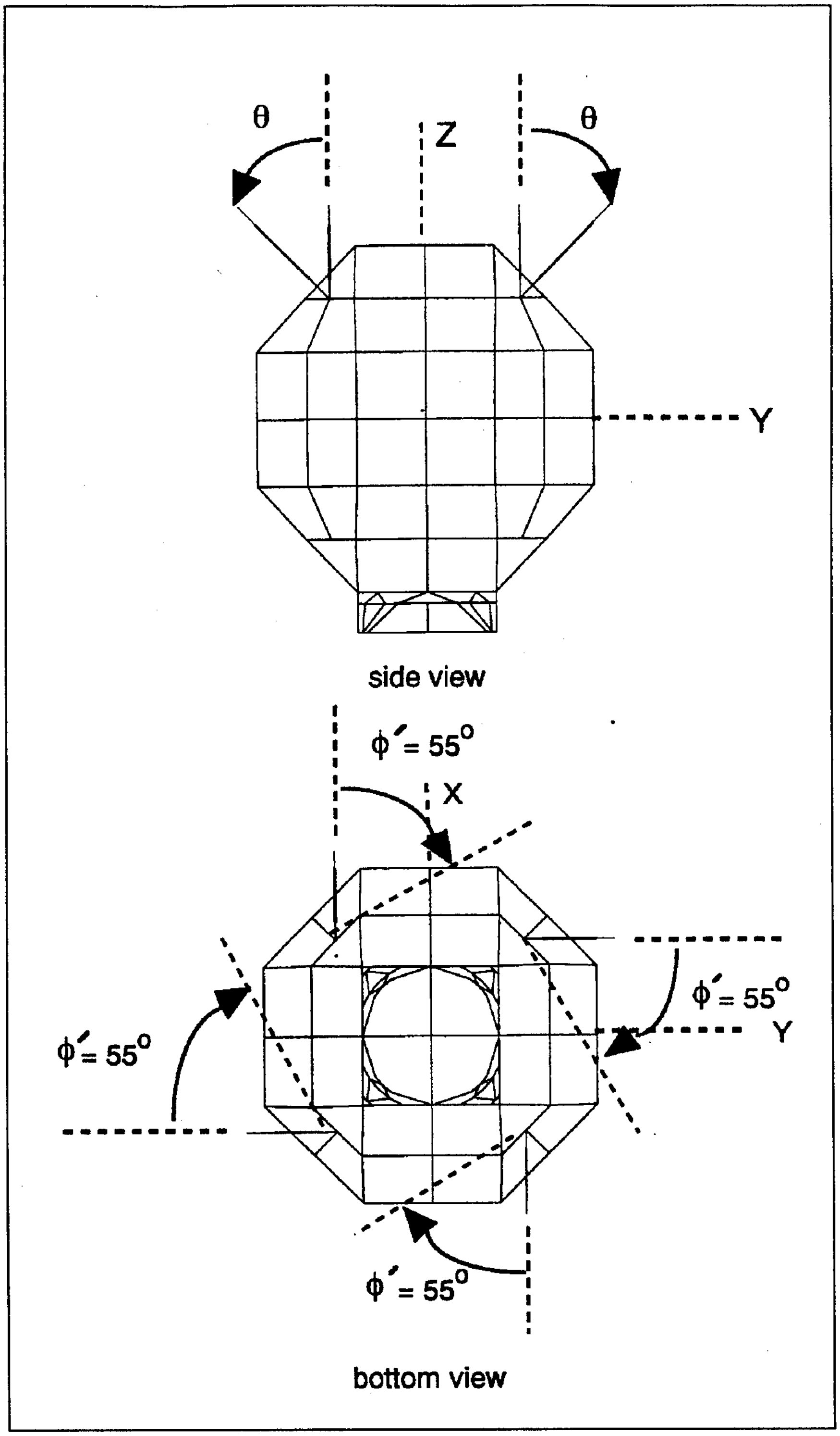

Figure 17. The Angles in ϕ with Nulls Better than -3dBi.

Detailed performance values for all the angles tested are presented in Appendix A.

3. Statistical Approach

Test of ϕ plane angles show that there are a number of configurations which produce sastisfactory performance. Radiation patterns of these configurations provide almost the same coverage. The minimum nulls do not exceed -3 dBi. As a result, the analysis so far does not identify a preferred value for ϕ. Thus, a statistical approach is employed. Since the satellite is a tumbling body, there is no way to tell which side of satellite body and which side of the radiation pattern will face the earth more often than any other. Consequently, the directive gain of the antennas can be treated as a random variable. The histograms of directive gain distribution over the θ and ϕ planes are plotted for each angle, and are grouped into two parts:

- More omnidirectional distributions.
- Non-omnidirectional distributions.

Angle configurations which do not provide minimum nulls better than -3 dBi are not considered. For an omnidirectional radiation pattern, directive gain distributions should show balance between positive and negative values. For the antenna angle orientation shown in Figure 18, the directive gain distribution (Figure 19) shows balanced values. Most other angle orientations did not show the same balanced distribution. Figures 20 and 21 are examples of unbalanced directive gain distributions,with negative inclined values.

Some of the angle configuration which have balanced directive gain distribution produce antenna input impedances that had smaller real part than the input inpedance for $\theta = 45°$ and $\phi = 0$ (47.6-59.4Ω). Figure 22 is an example of one of these with balanced directive gain distributions. For $\theta = 45°$ and $\phi = -25°$ (Figure 22) the antenna input impedance was 33 - j60.1. Therefore, directive gain distribution for $\theta = 45°$, $\phi = 0$ stood out among directive gain distributions of other angle configurations.

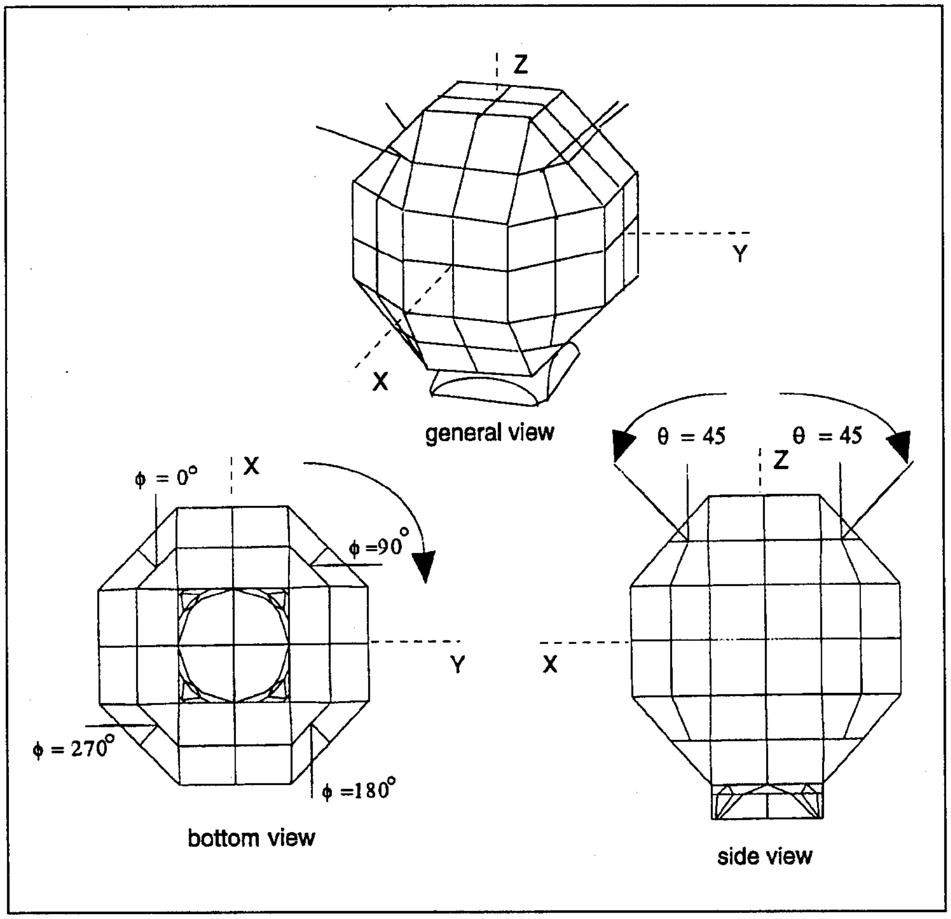

Figure 18. Final Orientation of the PANSAT Antenna System.

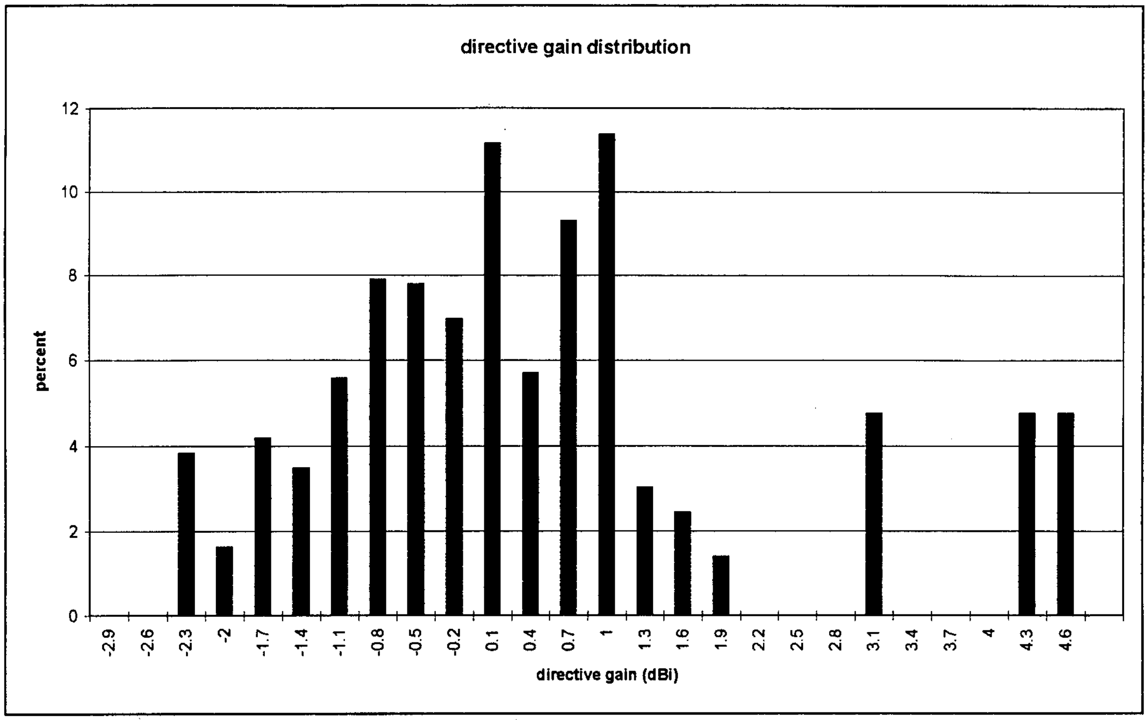

Figure 19. Directive Gain Distribution of the Final PANSAT Antenna System (θ=45°,ϕ'=0°).

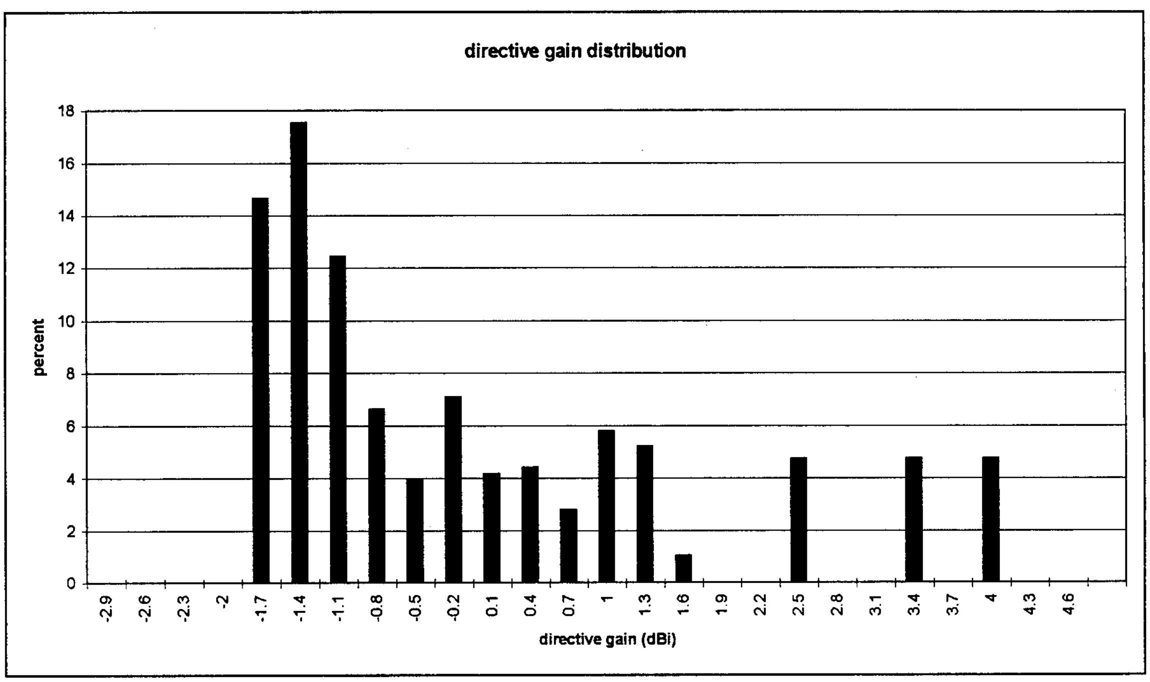

Figure 20. Directive Gain Distribution for $\theta = 10°$, $\phi' = 0°$.

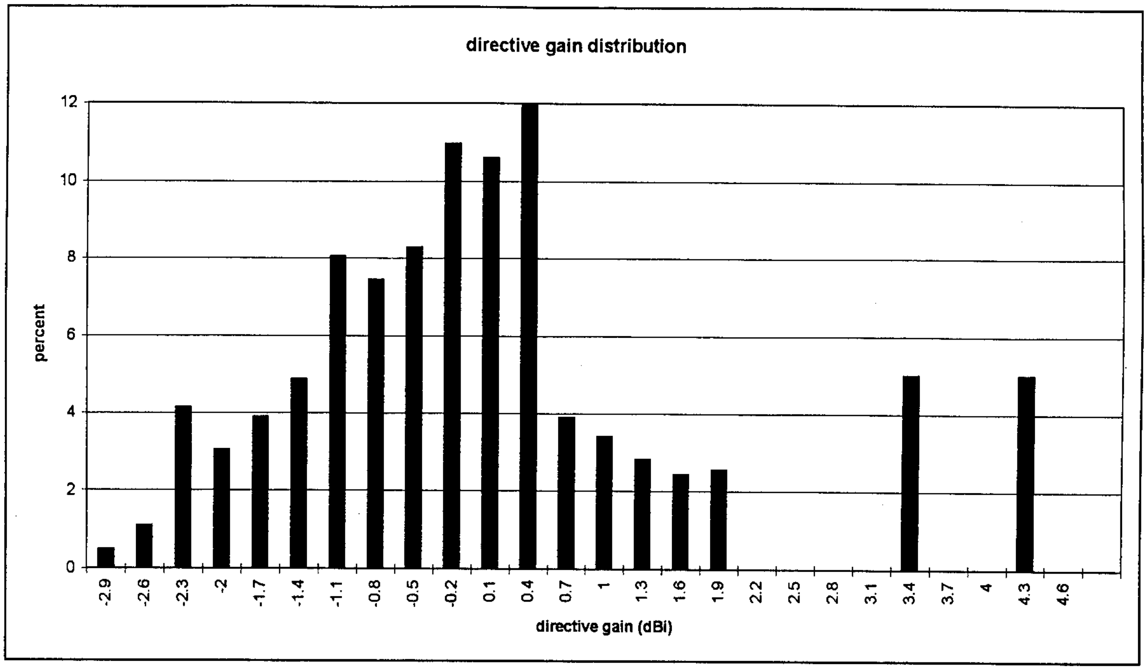

Figure 21. Directive Gain Distribution for $\theta = 45°$, $\phi' = 20°$.

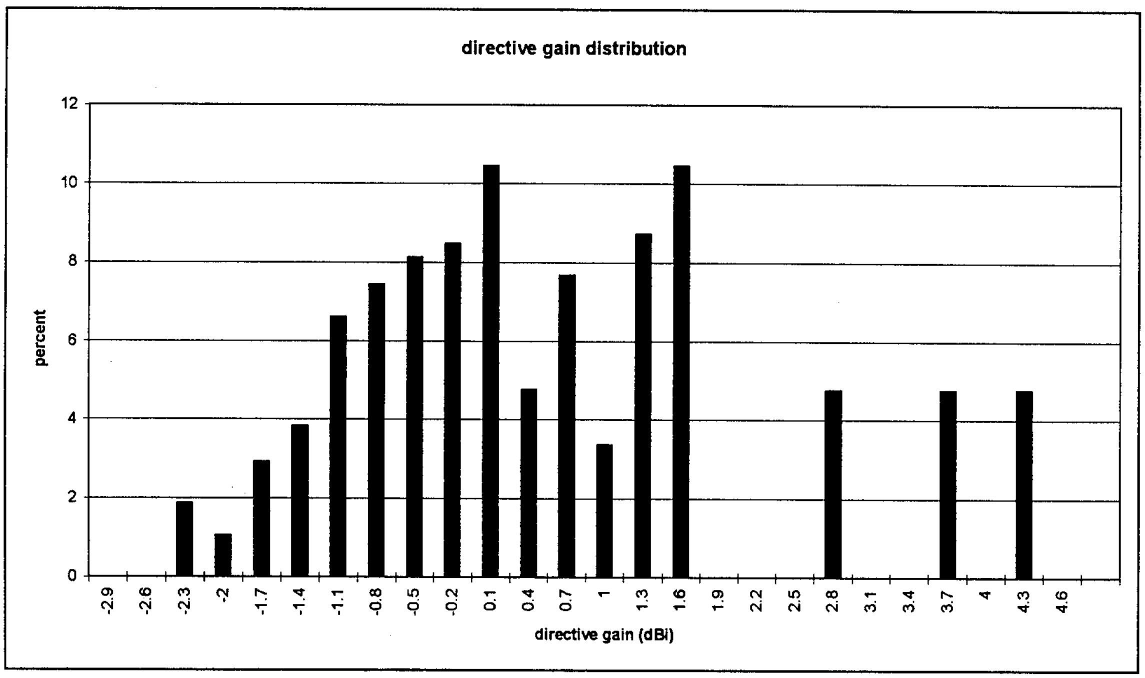

Figure 22. Directive Gain Distribution for $\theta = 45°$, $\phi' = -25°$.

4. Impedance

The location of the antenna and the angles in the θ and ϕ planes have been chosen. The next step is to adjust antenna input impedance. This is accomplished by repeatedly changing the lengths of antenna elements, noting the resulting input impedances. The real and imaginary parts of input impedance are shown in Figure 23. Detailed results are in Appendix B. The final decision on length of the antenna elements is explained in the next chapter.

D. SUMMARY OF THE MODIFICATION PROCESS

Before the modification process was started, the NEC PANSAT model without the LVI was run. The results of this were compared with the output for the model with the LVI. The main effect of the LVI showed in the minimum pattern gain for the same antenna locations of both models. Antenna positions on PANSAT, the length, and the angle orientation were treated as independent parameters in the modification process. These parameters affected the gain, pattern, and input impedance which were the dependent parameters. Each independent parameter was changed while others were kept constant. Performance was noted as the radiation pattern, polarization, antenna, and input impedance for each successive change. A gain histogram was used to determine the best orientation of the antenna elements because the performance analysis showed the similar results for most of the suitable angles.

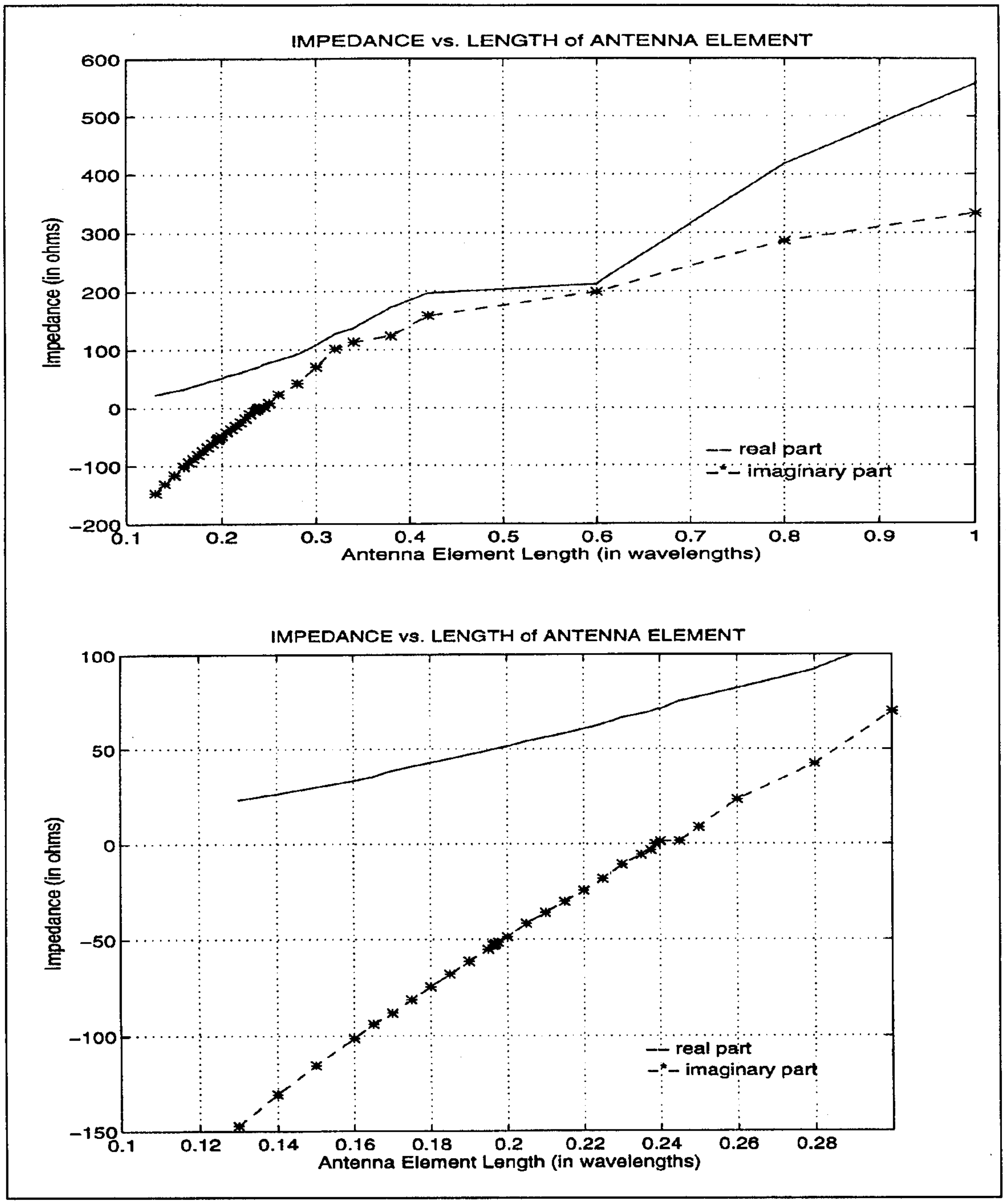

Figure 23.. Antenna Input Impedance vs. Antenna Element Length.

III. THE ANTENNA FEED SYSTEM

A. SPECIFICATIONS FOR THE PANSAT ANTENNA FEED SYSTEM

The PANSAT communication system consists of a transceiver rather than a separate transmitter and receiver, requiring a single 50Ω connection point. The maximum allowed VSWR is 1.4:1. The PANSAT antenna feed system must be easily mountable. In addition the cables and other materials used must meet standards required for a mission in space. Table IV summarizes the specifications for the antenna feed system.

One connection point.
50 Ω transmission lines.
VSWR = 1.4:1
Easily mountable
Suitable connectors and cables for space-based mission.

Table IV. Requirements of the PANSAT Antenna Feed System.

B. DESIGN GOALS FOR THE ANTENNA FEED SYSTEM

Mismatch at the antenna causes some percentage of the power to bounce back to the transmitter from the antenna. Some of this power, while bouncing back and forth, is lost due to attenuation on the transmission lines. For receiving, antenna mismatch causes some back scattering of the power captured by the antenna. Since the antenna elements

are connected via transmission lines, good impedance match will prevent power being lost between the antenna and either the transmitter or the receiver.

In this case antenna input impedance can be adjusted to become either 70.8-j0.8Ω at resonance or 50.1-j52.31Ω, depending on the length of the antenna elements. Table V shows the length of the antenna elements corresponding to these two impedances.

Impedance (Ω)	**Length**	
	m.	*l/λ*
70.8-j0.8	.164	.238
50.1-j52.3	.135	.196

Table V. Input Impedance vs. Length of Antenna Elements.

If the antenna elements with either of two input impedances are connected to a 50 Ω transmission line there will be a mismatch. The VSWR is 1.42 for 70.8-j52.3Ω and 2.74 for 50.1-j52.3Ω. This will cause reflections along the transmission lines. A matching network is needed to prevent power loss resulting from attenuation in the transmissioin lines. An antenna feed system is proposed for each input impedance. The comparative performance of the two feed systems is described at the end of this chapter.

C. DESIGN ALTERNATIVES

If 50.1-j52.3Ω input impedance is chosen, then a feed system using stub tuners is adequate. For 70.8-j0.8Ω, the feed system will need impedance transformers. The following two sections explain the two alternative impedance-matching systems.

1. Using Stub Tuners

The load impedance of 50.1-j52.3Ω is to be connected to a 50Ω coax cable. Adding a specific length of electrically shorted coax cable to a point at a certain distance from the load, results in a matched 50Ω input impedance. Figure 24 shows the length of the stub and distance from the load for the single stub matching system.

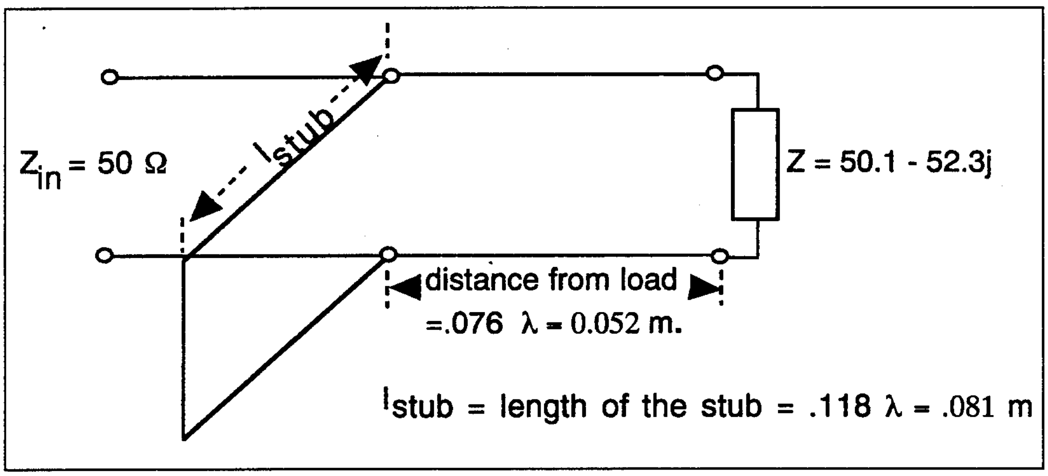

Figure 24. Single Stub Matching.

The single stub should be connected to each antenna element at the distance and length depicted in Figure 24. Figure 25 shows the feeding system of the antenna elements with stub tuners.

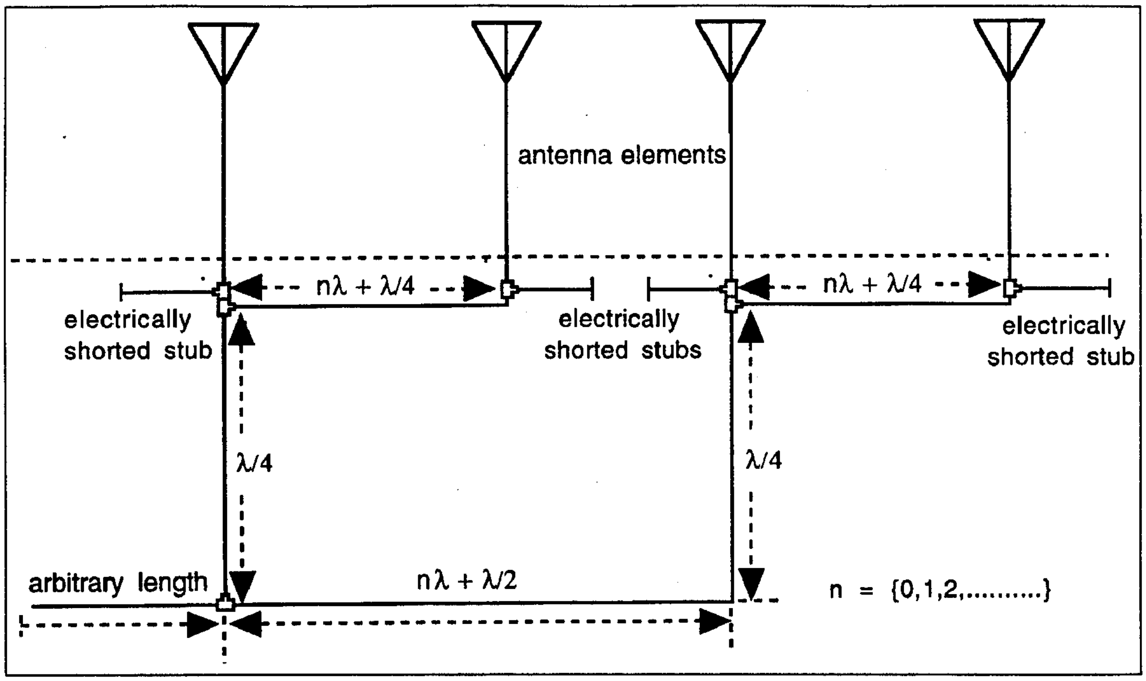

Figure 25. The PANSAT Antenna Feed System with Single Stub Tuners.

2. Using Impedance Matching Transformers

In this case antenna input impedance is to be adjusted to 70.9-j0.9Ω. The matchinng can be accomplished by using a quarter wave impedance transformer. The required impedance is $\sqrt{71x50} = 59.6\Omega$. This transformer can be easily realized in microstrip.

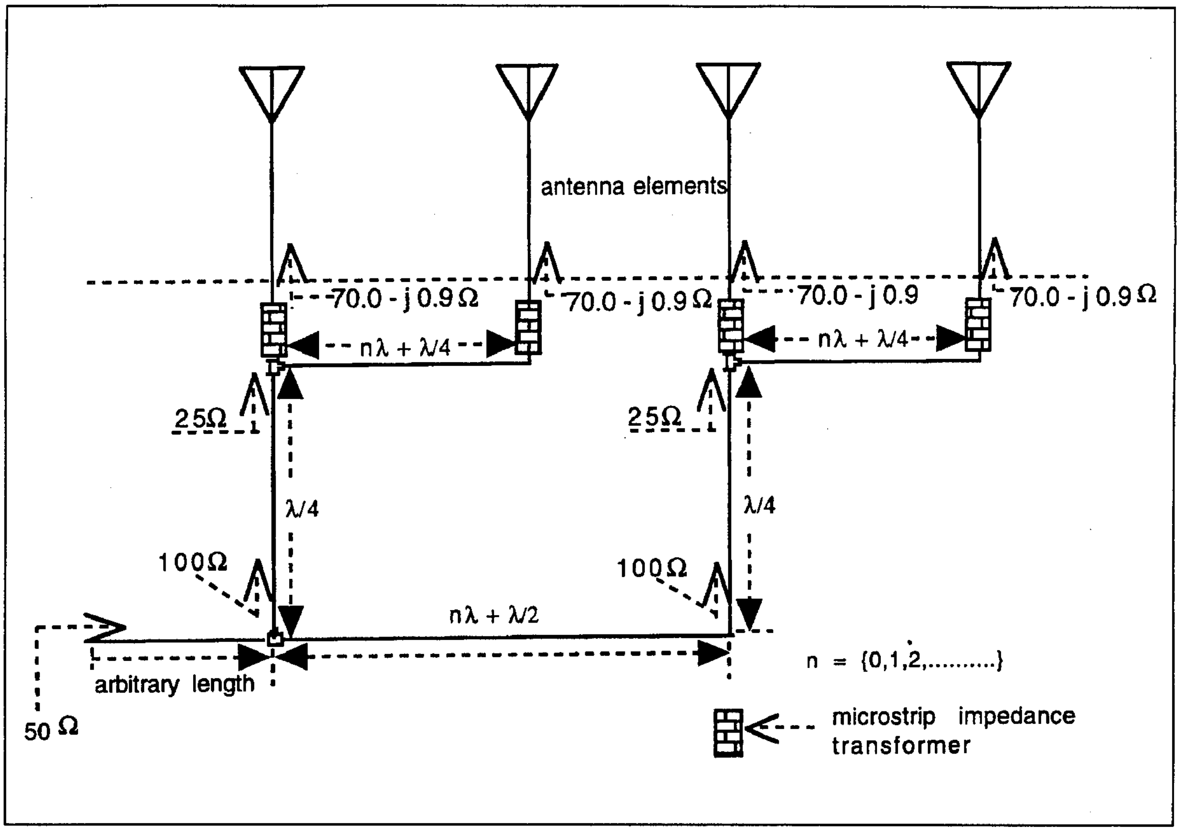

Figure 26. The PANSAT Antenna Feed System with 75Ω to 50Ω Impedance Transformer.

D. COMPARISON OF DESIGN ALTERNATIVES

Both of the designs make use of lengths of coax cable to feed each antenna element with a 90° phase shift relative to the adjacent element. These lengths also act as quarter wavelength transformers, which have characteristic impedance $z_0 = \sqrt{z_{in}\, z_{load}} = \sqrt{25x100} = 50\Omega$, where z_{load} is the impedance of load and z_{in} is the desired impedance to be observed from the source side of the quarter wavelength impedance transformer. The length of the transmission lines is important in both of the designs.

The frequency range is from $f_\ell = 435.25\,\text{MHz}$ to f_h = 437.75 MHz. When the lengths are calculated at the center frequency (f_0 = 436.5 MHz) the electrical length of the transmission lines will change with frequency

The band-limits wavelength ratios are:

$$\frac{\lambda_0}{\lambda_\ell} = \frac{f_\ell}{f_0} = 0.99713$$

$$\frac{\lambda_0}{\lambda_h} = \frac{f_h}{f_0} = 1.0022$$

Note the 0.3% error in the fixed length of transmission lines compared to the center frequency, f_0.

In the frequency range from f_ℓ and f_h, antenna input impedance changes. NEC is run with the frequency sweep of this range to observe the impedance changes. For the 0.164 m. long element, the impedance values varied from 70.7-j1.6Ω to 71-j1.5Ω. The 75Ω to 50Ω impedance transformer can tolerate this impedance variation. For the antenna element length of 0.135 m. the impedance show a variation from 50.04-j53.1Ω to 50.2-j51.6Ω. Since the length of the stub and the distance from the load is fixed in the single stub matching system, the electrical lengths will change with frequency, and the matched load impedance will not be exactly 50Ω. Table VI shows the variation of VSWR for the frequency range for antenna elements of 0.135 m.

Frequency (MHz)	VSWR (After the Stub)	Required VSWR
$f_h = 437.75$	1.024	1.4
$f_0 = 436.5$	1	1.4
$f_\ell = 436.25$	1.12	1.4

Table VI. VSWR vs. Frequency with .135 m. Antenna Element Lengths.

The single stub matching feed system can use the same type of coax cable. Ready-to-fly cables can be easily found. The microstrip impedance transformer must be space-worthy.

Both of the alternative feed systems meet specifications. One of the two antenna feed systems can be chosen after the length of the antenna elements is chosen.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY OF THE PROCEDURE

In this thesis the existing PANSAT antenna system was modified to overcome the effects of adding the LVI. The NEC program was used to predict the performance of the antenna elements as they are changed progressively to produce a design that provides optimum performance.

First, the location of the antenna elements was changed until the radiation patterns were acceptable and the minimum gain was greater than -3 dBi. Second, the orientation angle of the antenna elements was changed. A statistical approach was then used to find the orientation angle that gave the worst nulls less than -3 dBi.

Last, the length of the antenna elements was changed to achieve the input impedances of $70.8\text{-}j0.8\Omega$ or $50.1\text{-}j52.3\Omega$. Two input impedance values were chosen and two alternative antenna feed systems were proposed. After each iteration in position, angle and length, performance analysis was repeated to prove the design was acceptable.

B. FINAL ANTENNA DESIGN AND FEED SYSTEM

The tangential turnstile antenna of PANSAT is to be configured with four monopole antenna elements. Each antenna element is to be placed on the body of the PANSAT as shown in Figure 27.

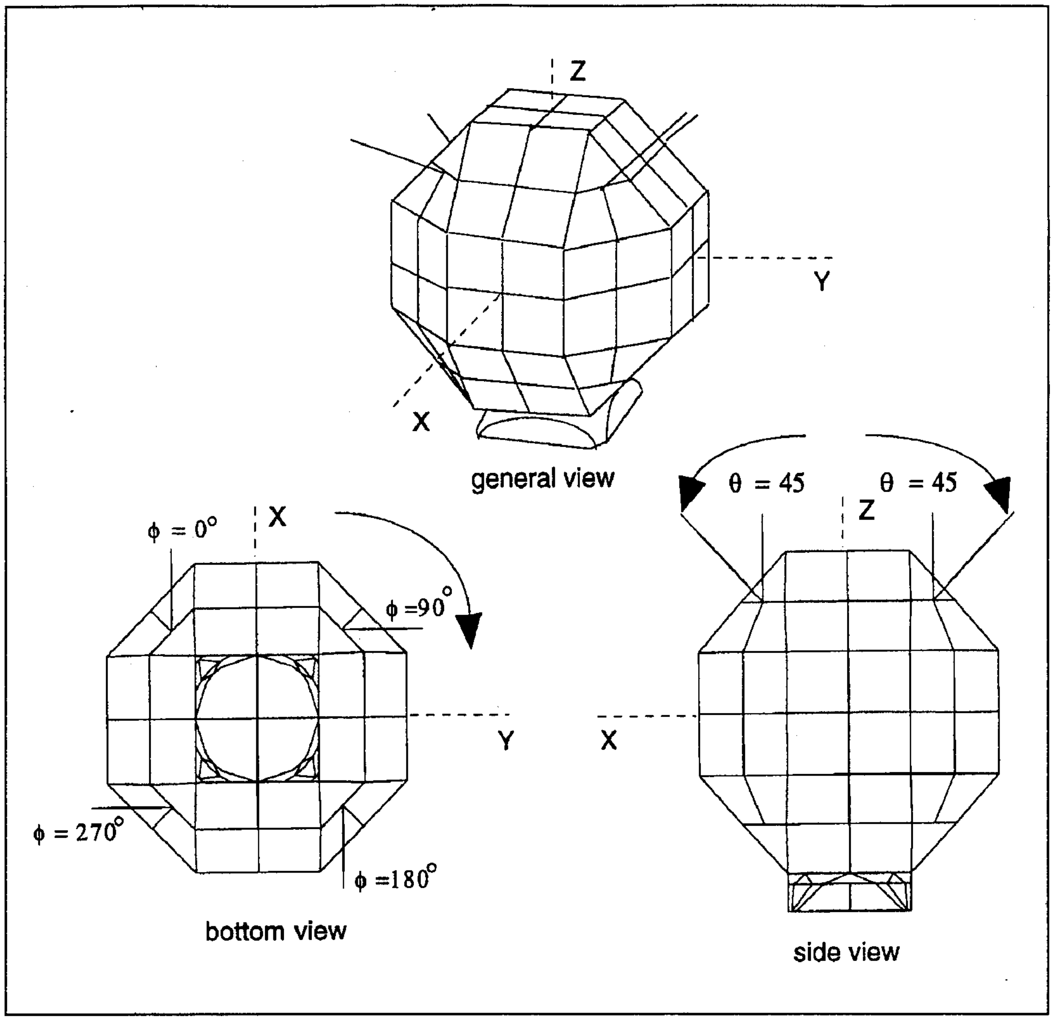

Figure 27. The Final Tangential Turnstile Antenna of PANSAT.

The final design produced a minimum gain of -2.7 dBi and maximum of 4.4 dBi. Two alternative feed systems are proposed with coaxial cable lengths chosen for the frequency of operation.

C. CONCLUSIONS

The final design of the tangential turnstile antenna for PANSAT can meet the mission specifications. The tangential turnstile antenna system can give near omnidirectional coverage for PANSAT, a tumbling satellite.

The proposed impedance matching systems with stub tuners or impedance transformers can meet VSWR requirements. Both of them meet the mission requirements of PANSAT.

D. RECOMMENDATIONS

The antenna system should be tested to verify the results of the NEC outputs. The satellite must be duplicated electromagnetically by simulating all conducting surfaces of the satellite. This model can be either metal or wood covered with metal, and must be removed from all reflecting and conducting objects by a distance which will ensure that the measured fields are not contaminated.

Antenna gain values change from -2.7 to 4.5 dB. If the reflection interference can be kept -10 dB less than then the minimum of the antenna gain variation, accuracy of the measurement becomes 5%. The external cables connected to body of the satellite must be arranged to be electromagnetically transparent. These cables should not carry any current from the satellite. If this can not be provided, the transmitting equipment can be mounted in the trunk of the satellite and be operated by battery.

Since no study based on pattern purity requirements is available at the time of this thesis, the level of the acceptable field contamination is not given here. The decision on

the impedance choice of the antenna elements must be made, which affects the choice of the antenna feed system.

APPENDIX A. PERFORMANCE OF CONFIGURATION ANGLES

Each angle configuration produces different results. Table VII summarizes the variations of angles and their corresponding performance values. For ϕ angle values only, the ϕ angle of the 0° phase fed antenna element is given. The other three elements are phase-shifted incrementally by 90°.

ANGLE (deg.)		GAIN (dBi)		IMPEDANCE (Ω)	AVERAGE GAIN (dB.)
θ	ϕ	Min.	Max.		
0	0	-2.7	3.6	44.4 - j 35.5	.93
5	0	-2.2	3.7	43.4 - j 48.2	.93
10	0	-1.7	2.7	46 - j 48	.93
15	0	-2	3.9	47.5 - j 51	.94
20	0	-2	3.9	49.1 - j 51.4	.94
25	0	-2.1	4	49.6 - j 53.6	.94
30	0	-2.2	4.1	50 - j 54.6	.95
45	0	-2.6	4.6	47.6 - j 59.5	.96
55	0	-3.2	4.7	44.5- j 61.1	.97
90	0	-4.9	4.6	12.6 - j 1	.94
135	0	-10.2	5.2	2.5 - j 6	1.0
45	10	-2.8	4.5	50.9 - j 58.6	.96
45	20	-2.9	4.6	53.6- j 58	.95
45	30	-3.1	4.7	55.4 - j 57.9	.95
45	45	-3.2	4.8	56.5 - j 58.2	.95
45	55	-3.1	4.8	56.1 - j 58.3	.95

Table VII. Performance Values vs. Configuration Angles.

ANGLE (deg.)		GAIN (dBi)		IMPEDANCE (Ω)	AVERAGE GAIN (dB.)
θ	φ	Min.	Max.		
45	65	-3.2	4.8	55.1 - j 58.1	.95
45	75	-3.4	4.8	53 - j 58.7	.95
45	90	-4.5	4.8	48.6 - j 59.3	.96
45	100	-5.4	4.8	65.1 - j 59.2	.96
45	110	-6.2	4.8	40.9 - j 59.	.96
45	125	-6.8	4.6	34 - j 59.2	.96
45	135	-6.1	4.4	29.3 - j 55	.95
45	140	-5.1	4.3	26.8 - j 52.8	.96
45	145	-3.4	4	23.8 - j 45.3	.98
45	150	-1.8	3.8	21 - j 36.3	1.0
45	155	-1.4	3.8	16.9 - j 17.8	1.1
45	160	-1.9	4.3	12.5 + j 8.5	1.4
45	-5	-2.5	4.4	45.8 - j 59.7	.96
45	-10	-2.6	4.3	43.8 - j 59.8	.96
45	-15	-2.6	4.2	41.8- j 60.1	.97
45	-20	-1.9	3.6	44.5- j 48.8	.93
45	-25	-1.6	4	37.5 - j 60.4	.97
45	-30	-2.6	3.9	35.3 - j 60.2	.97
45	-35	-2.6	3.8	33 - j 60	.97
45	-45	-2.8	3.4	28.5 - j 57.6	.96
45	-50	-2.9	3.2	26.1 - j 54.9	.97
45	-55	-3	2.8	23.7 - j 49.9	.98
45	-60	-3.1	2.6	21 - j 41.2	1.0
45	-65	-3	3.3	17.6 - j 25	1.1

Table VII. Performance Values vs. Configuration Angles.

ANGLE (deg.)		GAIN (dBi)		IMPEDANCE (Ω)	AVERAGE GAIN (dB.)
θ	ϕ	**Min.**	**Max.**		
45	-70	-2.6	4.3	12.9 + j 4.7	1.3
50	155	-2.3	3.8	20.2 - j 3	1.0
50	160	-1.5	3.9	16.6 - j 16.8	1.0
50	170	-5.5	4	15.2 - j 19.7	.94
50	-70	-2.8	2.5	17.2 - j 23.1	1.0
50	-75	-2.	2.8	13.2 - j 4.2	1.1
52	170	-3.5	4.4	11.9 + j 1.3	1.1
55	160	-4.2	3.8	21.3 - j 34.	.94
55	70	-.7	5.2	8.5 - j 29.6	1.4
55	-75	-2.7	2.7	17.7 - j 30.2	.96
55	-80	-2.6	2.8	14.5 - j 22.7	.97
55	-85	-2.4	3	11.3 - j 15.8	.98
55	-90	-2.2	3.9	46.7 - j 48.6	.93
60	-180	-12.7	4	15.2 -j 43.3	.81
80	10	-2	3.8	46.7 - j 49.1	.93
80	20	-2.1	3.8	47.7 - j 49.1	.93
80	85	-3.3	3.9	46.7 - j 48.6	.93
80	140	-3.8	3.8	39.4 - j 46.9	.92
80	150	-3.8	3.7	35.5 - j 46.7	.92
80	160	-3.6	3.6	34.7 - j 26.2	.91
80	170	-3.7	3.7	34.6 - j 46	.91
80	-10	-1.9	3.7	44.6 - j 68.7	.93
80	-20	-1.9	3.7	44.5 - j 48.8	.93
80	-85	-2	3.3	33.4 - j 46.7	.92
80	-90	-2	3.3	32.8 - j 46.5	.92

Table VII. Performance Values vs. Configuration Angles.

ANGLE (deg.)		GAIN (dBi)		IMPEDANCE (Ω)	AVERAGE GAIN (dB.)
θ	ϕ	Min.	Max.		
80	-100	-2	3.3	31.7 - j 46.2	.91
80	-135	-2.5	3.3	29.9 - 65.1	.91
80	-180	-3.5	3.6	32.8 - j 46.2	.92

Table VII. Performance Values vs. Configuration Angles.

APPENDIX B. INPUT IMPEDANCES VS. ANTENNA ELEMENT LENGTHS

Table VIII shows the impedance of the antenna elements for different element lengths at $\theta = 45^\circ$ $\phi = 0^\circ$, the parameters used for the final antenna design.

ANTENNA ELEMENT LENGTH		IMPEDANCE
in m.	in λ.	
.089	.130	23.0 - j 147.2
.096	.140	26.3 - j 130.8
.103	.150	29.8 - j 115.4
.109	.160	33.3 - j 101.3
.113	.165	35.4 - j 93.7
.116	.170	38.5 - j 88.0
.120	.175	40.5 - j 81.2
.123	.180	42.6 - j 74.4
.127	.185	44.8 - j 67.8
.130	.190	46.9 - j 61.3
.134	.195	49.1 - j 55.2
.134	.196	49.8 - j 53.1
.135	.196	49.9 - j 52.8
.135	.196	50.1 - j 52.3
.135	.197	50.4 - j 51.5
.137	.200	51.4 - j 48.6
.140	.205	54.0 - j 41.5
.144	.210	56.2 - j 35.9
.147	.215	58.4 - j 30.2
.151	.220	60.8 - j 24.3
.154	.225	63.3 - j 18.1
.158	.230	66.5 - j 10.7
.161	.235	68.6 - j 5.7

Table VIII. Input Impedances vs. Antenna Element Length.

ANTENNA ELEMENT LENGTH		IMPEDANCE
in m.	in λ.	
.163	.237	69.7 - j 3.3
.164	.238	70.8 - j 0.0
.164	.240	71.1 + j 1.3
.168	.245	75.3 + j 1.5
.171	.250	77.6 + j 8.8
.178	.260	82.3 + j 23.3
.192	.280	92.2 + j 42.2
.206	.300	108.1 - j 70.0
.219	.320	127.2 + j 101.4
.233	.340	136.8 + j 113.1
.261	.380	172.2 + j 123.4
.288	.420	196.8 + j 157.4
.412	.600	212.4 + j 198.7
.549	.800	418.1 + j 286.2
.687	1.00	557.6 + j 332.6

Table VIII. Input Impedances vs. Antenna Element Length.

APPENDIX C. NEC-4 INPUT FILE

```
CM  NEC-4  FILE
CE
GW1,2,.218,0.,-.108,.218,0.,-.024,.007,
GW2,2,.218,0.,-.024,.218,0.,.06,.007,
GW3,2,.218,0.,-.024,.218,-.09,-.024,.007,
GW4,2,.218,0.,-.024,.218,.09,-.024,.007,
GW5,2,.218,.09,.06,.218,0.,.06,.007,
GW6,2,.156,.092,.127,.156,0.,.127,.007,
GW7,2,.218,-.09,.06,.218,0.,.06,.007,
GW8,2,.156,0.,.127,.156,-.092,.127,.007,
GW9,2,.218,.09,.06,.156,.092,.127,.005,
GW10,2,.218,0.,.06,.156,0.,.127,.007,
GW11,2,.218,-.09,.06,.156,-.092,.127,.005,
GW12,2,.09,.09,.194,.156,.092,.127,.005,
GW13,2,.156,0.,.127,.09,0.,.194,.007,
GW14,2,.09,-.09,.194,.156,-.092,.127,.005,
GW15,2,.218,-.09,-.108,.218,0.,-.108,.007,
GW16,2,.156,-.092,-.175,.156,0.,-.175,.007,
GW17,2,.218,.09,-.108,.218,0.,-.108,.007,
GW18,2,.156,0.,-.175,.156,.092,-.175,.007,
GW19,2,.218,-.09,-.108,.156,-.092,-.175,.005,
GW20,2,.218,0.,-.108,.156,0.,-.175,.007,
GW21,2,.218,.09,-.108,.156,.092,-.175,.005,
GW22,2,.09,-.09,-.242,.156,-.092,-.175,.005,
GW23,2,.156,0.,-.175,.09,0.,-.242,.007,
GW24,2,.09,.09,-.242,.156,.092,-.175,.005,
GW25,2,.218,.09,-.108,.218,.09,-.024,.007,
GW26,2,.154,.154,-.108,.154,.154,-.024,.007,
GW27,2,.218,.09,.06,.218,.09,-.024,.007,
GW28,2,.154,.154,-.024,.154,.154,.06,.007,
GW29,2,.218,.09,-.108,.154,.154,-.108,.005,
GW30,2,.218,.09,-.024,.154,.154,-.024,.007,
GW31,2,.218,.09,.06,.154,.154,.06,.005,
GW32,2,.09,.218,-.108,.154,.154,-.108,.005,
GW33,2,.154,.154,-.024,.09,.218,-.024,.007,
GW34,2,.09,.218,.06,.154,.154,.06,.005,
GW35,2,.218,-.09,-.108,.218,-.09,-.024,.007,
GW36,2,.154,-.154,-.108,.154,-.154,-.024,.007,
GW37,2,.218,-.09,.06,.218,-.09,-.024,.007,
GW38,2,.154,-.154,-.024,.154,-.154,.06,.007,
GW39,2,.218,-.09,-.108,.154,-.154,-.108,.005,
GW40,2,.218,-.09,-.024,.154,-.154,-.024,.007,
GW41,2,.218,-.09,.06,.154,-.154,.06,.005,
GW42,2,.09,-.218,-.108,.154,-.154,-.108,.005,
GW43,2,.154,-.154,-.024,.09,-.218,-.024,.007,
GW44,2,.09,-.218,.06,.154,-.154,.06,.005,
GW45,2,-.09,.218,-.024,0.,.218,-.024,.007,
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